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BASIC PRINCIPLES OF CONCRETE MAKING

BASIC PRINCIPLES OF CONCRETE MAKING

BY

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WITH AN INTRODUCTION BY

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PREFACE

Too long has the quality of concrete in our important structures been determined by the desire or whim of the man at the mixer. It is time that the engineer or superintendent responsible for the other features of the construction project assume also responsibility for this important detail.

The practice of allowing the mixer foreman to regulate the amount of water has been fostered by the use of fixed proportions of cement and aggregate, chosen without regard to the conditions of placement. While the evils of this practice have been quite generally recognized, the tendency to reject it for a better practice has been slow in developing. This is partly due to a natural reluctance to change, and partly to the confusion and complication of detail which have surrounded the alternative methods heretofore proposed.

It is the purpose of this book to present the underlying principles of concrete mixtures in such a way that those in charge of construction will not only recognize their responsibility for the quality of concrete, but will at the same time find a simple and direct method of meeting the responsibility.

The text is not written for the man at the mixer or the concrete finisher. It presumes a familiarity with concrete construction and some knowledge of the literature. Once the engineer or superintendent thoroughly understands the basic principles, he should be able to write the necessary instructions or specifications to apply these principles to a particular set of conditions through the personnel of his own organization.

The larger part of this text first appeared as a series of articles in *Engineering News-Record* during April and May,

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1929. The requests for reprinting the articles in assembled form have been too numerous to ignore. Except for some further data on strength and permeability, which have been added, only such modifications and rearrangements have been made in the original text as were necessary to adapt it to the new form.

Grateful acknowledgment is made to members of the research staff of the Portland Cement Association for suggestions and criticisms, and to Mr. F. E. Schmitt, Editor, *Engineering News-Record*, for searching and constructive criticism.

F. R McM.

Chicago, Ill.,
September, 1929.

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INTRODUCTION

In order to give sound guidance to the worker in concrete, one of the keenest students of concrete-making has set down in this book what many thousands of laboratory tests and hundreds of observations on field jobs and structures taught him about proportioning. If these teachings are applied consistently they will bring definite improvement in an art whose operations form a large part of modern engineering construction.

An interesting set of events lies back of the writing of the book and gives character to its message. Many calls came to the editorial office of *Engineering News-Record* for assistance in unraveling and interpreting the complex doctrines of concrete proportioning current in recent years. These new doctrines had done away with the practice of prior decades to use a fixed mixture, such as the long-famous 1:2:4, but in doing so they had replaced rule-of-thumb by scientific riddles. The result was confusion. There was bickering between field engineers and construction men, and excited controversies arose over poor work done under the new systems of proportioning.

The situation became so serious that the editor, the late Frank C. Wight, proposed to invite a clear-sighted investigator and engineer to prepare a modern primer which should illuminate the subject thoroughly and sweep away the growing confusion. What Mr. Wight sought for was a simple exposition of the fundamental elements of the concrete-making art as derived from and supported by careful laboratory research. Fatal illness overtook him before he could carry the plan into execution. Its importance was obvious, and soon after Mr. Wight's death, in September, 1927, the writer discussed the plan with F. R. McMillan, research director of the Portland Cement Association, and urged him to undertake the task. Mr. McMillan finally agreed to do so, in his private capacity. Though he had access to the wealth of test data in the Association's laboratory files, he nevertheless found the enterprise unusually difficult, and only after some fifteen months, during which he prepared at least three successive drafts, did he finally complete it.

His work turned out to be an even more important contribution to knowledge of concrete than had been anticipated. It was printed as a series of five articles in *Engineering News-Record* during April and May, 1929, but even before the last article appeared there came numerous demands for a collected printing. Since the far-reaching effect which the work promised to exert upon concrete practice made a permanent binding desirable, the book form was adopted. Some revision resulting from a critical review of the original text renders the book clearer and more complete than the articles as first published. Nevertheless, an appraisal which appeared as an editorial in *Engineering News-Record* of April 11, 1929, remains pertinent and is therefore reproduced in the following pages.

Supplementing that appraisal it may be remarked that the properties grouped under the term "workability" are among the major uncertainties of the art. Much effort is being put upon their study and upon the interpretation of the term under different conditions, for it clearly has many meanings. But on any specific job the teachings of this book can be applied safely and surely by the man who, understanding the job and its demands, uses his finger knowledge to judge of the consistency best suited.

F. E. Schmitt

New York, N. Y.
September 26, 1929

BASIC PRINCIPLES

(An Editorial from *Engineering News-Record,* April 11, 1929)

For some time back the concrete-making art has been floundering in certain respects. While on the whole advancing, it has done so with uncertain and sometimes retrograde steps. Excellent concrete has been made, and also very bad concrete. A dam in the West leaks uncomfortably, though built with the aid of what was believed to be the most refined scientific effort to produce a mixture of ideal excellence and economy. A dam in the East is scaling and crumbling on its surface, though only a few years old. A bridge whose construction was scientifically supervised so that it might be not only strong but of perfect appearance turned out to be blotchy and honeycombed when the forms were stripped.

There is a reason for these conditions: the art has been made too complex. The belief has grown up that intricate charts, formulas and slide rules are necessary preliminaries to the production of good concrete. Inherently the art is as simple as it was many years ago, when it was clearly understood that the necessary and sufficient ingredients of concrete are cement, sand, stone and water, together with common sense and judgment; but recent practice has tended away from this simplicity. For example, on one important undertaking the field engineer devoted his major attention to sampling the successive shipments of gravel and sand, screening and sieving the samples, making careful computations to determine how they should be mixed, and finally finding by trial how little cement and water he could add to this mixture and yet meet a certain slump requirement. If good concrete is obtained in spite of such involved procedure, it is only by good fortune and excellent field judgment.

In short, fineness modulus, surface area and like devices have badly bedeviled an art that at bottom remains intensely practical despite its scientific foundation. It is timely that these conditions be corrected by a return to simplicity of understanding and practice. To put this within easy reach is the objective of

F. R. McMillan's articles on "Basic Principles of Concrete-Making."

With brilliant clearness of view the author has reduced the subject to its fundamentals; and in so doing he has written a document of long-time value. For the complex theories and rules of the recent past he substitutes a simple statement calling for two steps: first, the selection of a cement paste of a known degree of wetness, which according to Abrams' well-known law predetermines the qualities of the final concrete; and second, the addition of sand and stone in amounts that will fill this paste as thoroughly as possible and produce a fully plastic, workable mass. Note the significant last clause; its full meaning, emphasized farther on, carries the key to the statement of concrete doctrine. Nothing could be simpler. And a striking feature of the matter is that practical field judgment appears to be the best (if not the only) guide in deciding on the second step. Thus the practical concrete man returns to his own, but with greater power; instead of having to depend on unaided experience he now has a definite yardstick by which to rate his material—namely, the water content of his paste.

Perhaps one of the points of greatest value of the entire doctrine is that it tends to restore the field worker's confidence in his practical judgment. It shows him that his intuitions still are valid, and that he therefore has a real responsibility for results in the quality and appearance of concrete.

It is worth noticing that the new statement of principles is derived from a new conception of concrete-making. In the past it has been customary to conceive of concrete as something produced by taking a mass of aggregate and filling its interstices with a mortar, which in turn was produced by taking a mass of sand and filling it with cement. The conception on which Mr. McMillan bases his statement of principles is the reverse of this: a batch of paste of fixed water ratio is prepared, and the aggregates are then embedded in the paste. The new conception is as significant in its practical application as it is logical in its relation to the chemical and mechanical factors involved.

In reading the statement of principles some associated facts will occur to anyone who follows the author's exposition closely. One of them is that workability will not always mean just the same thing; its meaning will vary slightly with the conditions of placement—though, of course, it may never be stretched to

include a distinctly wet mix, nor a dry mix except when thorough tamping or equivalent mechanical consolidation is to be used.

Another and even more important fact is that, after all, the most suitable wetness of the paste and the best amount and grading of the aggregates are not independent variables. They influence each other markedly. But any attempt to evaluate both variables by one single step is likely to fail in practice. One of the two variables must be fixed upon first, at least tentatively, and the other then determined from it, subject perhaps to a readjustment on second trial. In the practice of recent years the attempt was usually made to determine first the aggregate combination. Mr. McMillan by reversing this practice makes what seems almost a stroke of genius—but after all something eminently sane and sensible, since it begins the concrete-making process with the active element, the cement paste, to which the aggregates serve only as diluents and as body-forming additions.

One term bound up in the statement of principle is perhaps more important than any other: the term *plastic homogeneous mixture.* So soon as the reader has thoroughly grasped the significance of this term he will be beyond danger of missing the author's essential instruction. A plastic and homogeneous mixture is freely but sluggishly mobile, is full throughout, and is proof against segregation so far as the immutable laws of gravity permit. Such a plastic mixture will make uniformly good concrete, of properties determined by the degree of moisture of the paste. That, in brief, is the doctrine of the articles.

It remains to add that of course there are differences between cements; that aggregates differ; that grading is not without vital meaning; and above all that mixing, transporting, placing and curing must be done with care and excellence. All these are vitally important matters, but they are matters which the able engineer and concrete-worker will find no difficulty in handling.

Be it understood that the articles do not purport to set forth all the facts and secrets of concrete, neither of the present nor of the probably much greater future; they do, however, go far toward eliminating some of the mystery that has come to surround the subject, and they simplify effectively the principles of proportioning. In future we shall doubtless know much more about watertightness, strength, plasticity, texture and control of properties. But regardless of such advances, the basic principles now set forth are likely to remain fundamental.

BASIC PRINCIPLES OF CONCRETE MAKING

CHAPTER I

THE PHILOSOPHY OF CONCRETE MIXTURES

A Resumé of the Principles of Concrete Making to Give the Reader a Background for the Details to Follow

To provide continuity of thought and assist the reader to visualize the scope of what is to follow, this brief resumé is given. This chapter is in effect a summary of the entire text stripped of explanation, proof, or illustration. It may profitably be read occasionally during the perusal of the text and again as a final summary when the study is completed.

Cement Paste the Basis of Concrete Quality.—Expressed in the simplest terms, concrete is a mass of aggregates held together by a hardened paste of portland cement and water. The distinction between these two elements of concrete should be kept clearly in mind, as it is the basis upon which the principles and methods of this text are developed. The aggregates are essentially inert. The paste is the active element.

There are, of course, certain properties of the aggregates which influence the properties of the concrete; these will be brought out later in the text. But at this point it is necessary only to observe that, important as these properties are, they should not be allowed to obscure the fact that the concrete derives its useful properties mostly from this hardened cement-water paste.

For a complete understanding of the properties of concrete, we must first understand the properties of the paste. Clearly, if strong concrete is desired, the paste must develop high strength when hardened. If watertight concrete is required the hardened paste must itself be watertight.

Properties of the Cement-water Paste. When portland cement is mixed with enough water to form a paste, the compounds of the cement react with the water to form new compounds which adhere to each other and to the aggregate particles to form the binding medium which gives concrete its useful properties. To complete these chemical reactions, three things are required: (1) time, (2) favorable temperatures and (3) the continued presence of water. When these three conditions are fulfilled, the concrete is said to "cure" properly; in their absence the curing is said to be deficient.

A cement paste in which the reactions have progressed only slightly (whether due to low temperatures, to insufficient time or to loss of water from the mass) cannot have the strength or watertightness of one in which the chemical changes are more complete. Thus, age and curing conditions become essential factors in the quality of the hardened paste. Likewise, those characteristics of the cement which influence the rate of chemical combination are factors. Some cements gain their strength more rapidly at first, while others show greater increase for longer periods.

Another factor in the quality of the hardened paste is the relative proportions of cement and water. This obviously affects the properties of the paste just as the propreties of mixtures, alloys, or other combinations of materials are affected by the proportions of the ingredients. Only a certain amount of water can be combined with the compounds of the cement, and any water in excess of this amount dilutes the mixture and reduces its potential strength, watertightness and durability.

Thus it is seen that the properties of the hardened paste are dependent upon these three factors:

1. The characteristics of the cement.
2. The relative proportions of cement and water.
3. The completeness of the chemical combination between the cement and water.

It is through the control of these factors that the engineer can control the ultimate usefulness of his concrete structures.

Combination of Aggregates and Paste.—When the aggregates and cement paste are mixed to form concrete, the space between the aggregate particles must be completely filled with the paste. Further, as a practical matter the paste must be of such consistency that the mixture is plastic and remains homogeneous during transporting and placing.

With clean, impervious aggregates, such a mixture will give a concrete in which the permeability is determined by the watertightness of the hardened paste. If, in addition, the aggregates are themselves of durable mineral composition, the resistance of such a concrete to weathering will be determined largely by the resistance of the hardened paste to weathering. Also, the strength of such a mixture will be determined by the strength of the paste. When the aggregate particles themselves are weak or of such a character as to offer little bond with the paste, the strength of the concrete will naturally be less than for normal aggregates, but even here, the strength of the concrete is influenced by the strength of the paste, for a strong paste offers very great support to the aggregates when the particles are thoroughly surrounded.

From the foregoing it can be seen that proportioning concrete for a given purpose requires two distinct steps: first, the selection of that proportion of water and those conditions of curing which, for the given cement, will produce a paste to meet the requirements for the particular structure as to strength and watertightness, or weather resistance; and second, finding a combination of

aggregates which, with water and cement in the selected ratio, will give a mixture that is plastic and that will remain homogeneous during placing and through the setting and hardening period.

In these two steps is embodied much of the philosophy of concrete mixtures. By controlling the quality of the paste through the selection of the proportion of water and cement and the degree of curing, the potential quality of the concrete is determined. By adjusting the proportions of aggregates and paste to give uniformity and homogeneity, this potential quality can be fully realized.

Importance of Plastic and Homogeneous Mixtures. It is vital throughout this discussion to keep in mind the necessity for plastic and homogeneous mixtures, for it is only with such mixes that the laws of strength and watertightness of the cement paste can be applied to the concrete as a whole. A plastic mix is one which can be readily molded—that is, it flows sluggishly but without segregation of the water or the fine materials from the coarse.

A plastic consistency is an intermediate one, separating the wet or fluid consistencies on the one hand from those of the stiff, or granular type, on the other. In placing it requires some spading or working to insure filling the angles of the form and complete embedment of reinforcement, but does not require the constant ramming needed for dry consistencies. Plasticity involves more than a difference in water content. It involves the amount and character of the aggregates as well as the amount of water and cement. The factors governing the plasticity of a concrete mixture may be stated as follows:

1. Relative quantities of paste and aggregates.
2. Plasticity of the paste itself.
3. Grading of aggregates.
4. Shape and surface characteristics of aggregate particles.

For any given paste, that is, a quantity of cement with its definite proportion of water, decreasing the amount of paste with respect to the quantity of aggregate stiffens the mixture, and increasing the amount of paste renders the

mix more fluid. If the quantity of paste is reduced to the point where there is not enough to fill the spaces and actually float the aggregate particles, the mix will become granular or harsh and will be impossible of proper placement.

Similarly, for a given quantity of paste and aggregate the plasticity of the mix will depend upon the relative quantities of cement and water in the paste. A paste that is high in cement and low in water content will itself be stiff and cannot carry much aggregate without becoming so stiff as to be wholly unplaceable. On the other hand, if the cement content of the paste is low and the water content high, the paste may be so thin and watery that it will be unable to hold the aggregates in that cohesive mass which is the very embodiment of plasticity.

The grading of the aggregates affects the plasticity of the concrete: (1) by affecting the quantity of paste necessary to fill the spaces thoroughly and surround the aggregate particles completely, and (2) by affecting the resistance which is offered to the mobility of the mass through the varying combinations of sizes.

As in the case of grading, the shape and surface characteristics of the particles affect the plasticity of the mix through their effect on the amount of paste required and on the friction between the particles as the concrete is molded. Angular particles or those with rough surfaces require a greater amount of paste for the same mobility of mass than is necessary for well-rounded particles or those with smooth and slippery faces, other conditions remaining the same.

Wet and Dry Mixes to Be Avoided.—The importance of plastic mixes, as a factor both in the construction operations and in extending the useful life of the structure, cannot be over emphasized. For proper placement it is essential that mixes be of such plasticity that they can be molded readily into the corners and angles of the forms with the assurance that every portion of the space will be thoroughly filled with the concrete and that there shall be

no honeycombing in the mass. Thus, dry, non-mobile mixtures which are difficult to place must be carefully avoided, both as a convenience in placing and to assure a uniform and homogeneous mass in which all the space between the aggregate particles is filled with a cement paste of the desired quality.

Equal care must be taken to avoid the overwet mixes. While mixes of this type are easily placeable and therefore all too commonly used, they are a serious menace to the life of a structure exposed to the weathering action of the elements. The segregation of materials in handling in such mixes causes honeycombed spots which offer the first point of attack for water and frost. Also, the accumulation of water and fine materials at the surface as the placing of such mixes progresses results in laitance layers and porous concrete immediately below. These segregation effects are the causes of the most widely observed form of disintegration.

Many have formed the impression that the present-day agitation for control of the quantity of mixing water necessarily means dry, unplaceable concrete. Nothing could be farther from the truth. This misconception arises largely from the habit of thinking of concrete solely in terms of certain arbitrary proportions, in which case, of course, the only way to change the consistency is to change the water content. Once the habit of relating all discussions of concrete to experience with 1:2:4 or other fixed proportions is thoroughly shaken off, it is seen that *control of the quantity of water means simply fixing the potential quality of the concrete.* Thus, with the water quantity fixed in terms of the cement, the consistency must be controlled through the relative quantities of aggregate and paste and proportions of fine to coarse aggregate. Naturally, the consistency to use depends upon the requirements of the work; the concrete should be sufficiently mobile to mold properly, but not of such fluidity that the material will segregate either in placing or through settlement after once in place.

CHAPTER II

COMBINED AND UNCOMBINED WATER

The detailed study of the principles which have been briefly outlined in Chapter I may well begin with the consideration of the part which the water plays in the making of concrete. As brought out in Chapter I, the proportion of water to cement is one of the three factors which determine the quality of the paste. This water-cement ratio was also shown to be a significant factor in the consistency of the concrete, affecting to an important degree the placeability of the mixture. Thus, we see that the water serves both as a chemical constituent of the active paste and as a vehicle to make the concrete more readily placeable.

The two-fold purpose of the water is nicely brought out by the diagrammatic representation in Fig. 1 in which five mixtures are shown all mixed with sufficient water to give a uniform consistency—slump 3 to 4 in. The mixtures selected—1:1:2, 1:1½:3, 1:2:4, 1:2½:5, and 1:3:6—required respectively, 4½, 5, 6, 8, and 10 gal. water per sack cement to give this 3 to 4-in. slump. It must not be assumed that these mixtures all have exactly the same placeability because they have the same slump, for this is not possible with such a wide range in cement content. It can be seen, however, that for certain types of work, as for example, a masonry wall or footing, these mixtures could each be used satisfactorily. This fact must be kept in mind, for the full significance of the study in Fig. 1 would be lost if the mixes were not comparable on some basis. The basis here adopted is that they might, so far as placeability is concerned, be equally suitable for *some* class of work. The comparison then can be fairly made

as to their relative suitability, considering strength, watertightness, and cost.

Neither should it be assumed that because the familiar arbitrary mixtures have been used in this illustration that these are necessarily the most suitable. These have been selected as they are most familiar to those experienced in concrete work. With these particular aggregates, as with most others, slightly higher proportions of the fine aggregate with respect to the coarse would prove more suitable for the ordinary concrete work. However, the mixtures all had sufficient paste to completely fill the spaces between the aggregate particles and with care could be used in mass construction. The interpretations from this diagram, to follow, and any further references to it in the text can be applied to concrete mixtures as a whole only when the concrete has been so placed as to avoid separation or segregation of the ingredients, and to give a mass that is uniform and homogeneous with all the spaces completely filled with paste.

Construction of Fig. 1.—The abscissas in Fig. 1 have no significance. The mixes are merely spaced equally. The ordinates of the lower diagram represent the absolute volumes (volumes of solid matter) of the ingredients in a unit volume of freshly mixed concrete. The 1:1:2 mix, for example, is seen to consist of 66 per cent aggregate, 16 per cent cement and 18 per cent total water, and the 1:3:6 concrete, at the opposite side of the diagram, of 76 per cent aggregate, 6.7 per cent cement and 17.3 per cent total water. These figures ignore the small air voids that are apt to occur, as in these mixes they are negligible. For mixes of stiffer consistency or with a very high proportion of fine aggregate, the air voids might be of such magnitude as to require their inclusion. This matter of air voids will receive separate consideration later in the text.

In the upper diagram the cement paste alone has been analyzed in the same manner as the concrete in the lower portion. Thus, the ordinates represent the absolute volume

of the cement and water in a unit volume of the paste. For example, the 34 per cent of paste in the 1:1:2 mix is now represented as 100 per cent, of which about 47 per cent is cement and the balance water.

It will be noted in both portions of Fig. 1 that the water is divided into combined and uncombined. This shows graphically the two-fold part which the water plays in concrete mixtures. The amount of water which can go

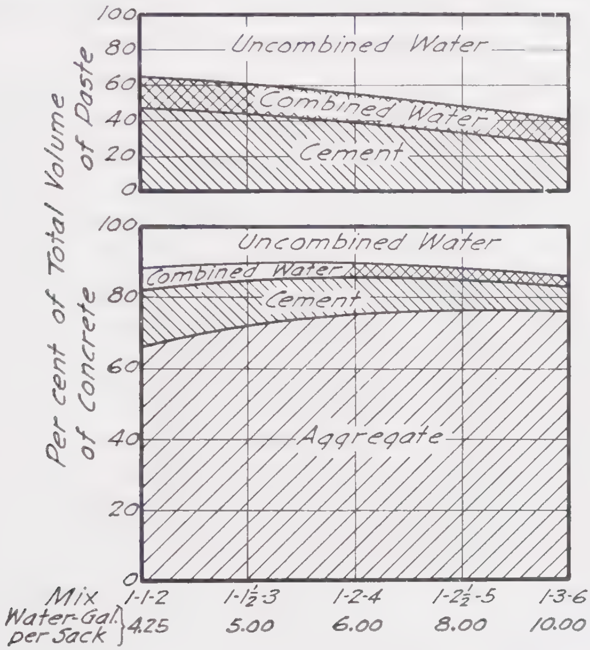

FIG. 1.—Analysis of concrete mixtures of uniform consistency. Slump 3 to 4 in.

into combination with the cement is brought out later. It can be stated here that were there only sufficient water for the chemical combination, the concrete would be wholly unplaceable. It is significant that this extra water, which makes possible the effective and economical use of concrete, also introduces most of the difficulties encountered in its use.

Cement Quantity and Water-cement Ratio.—A noteworthy feature of the lower diagram in Fig. 1 is the relative

quantity of aggregate, cement, and total water (combined and uncombined) for the different mixes. It will be seen that the total quantity of cement and aggregate is quite uniform in the five mixes, leaving approximately the same total quantity of water in the various mixes. Stated otherwise, this means that in order to produce a fixed consistency (3 to 4-in. slump in this case) about the same total amount of water is required per unit volume of concrete for rich and lean mixes alike. This shows the intimate relation between cement quantity and water ratio.

The foregoing statement applies to Fig. 1 in which the volume of concrete is the same for the different mixes. The same thought can be expressed differently if the quantity of aggregate remains fixed. For this case, and with the proportion of fine to coarse aggregate remaining unchanged, any change in the quantity of cement must be offset by a change in the water quantity to maintain constant consistency. Thus, increasing the cement quantity permits a reduction in the water quantity, or a reduction in cement quantity requires an increase in the amount of water. This explains why lean mixes require more water per sack of cement than rich ones for workability. This whole matter is of great importance and will be more fully considered later.

Amount of Combined Water.—The most significant relation exhibited by the lower diagram of Fig. 1 is the proportion of combined and uncombined water with respect to the other elements of the mix. The quantities of combined water which were plotted in the diagram are those which would exist at one particular age and under a particular set of curing conditions.

The quantity of combined water may vary over a wide range, being influenced by the fineness and composition of the cement, the quantity of water mixed with the cement, the age and curing conditions. Water which remains in the concrete in some degree of fixity at one temperature and humidity passes off readily at some higher temperature or lower humidity. Tables I, II and

Table I.—Quantity of Combined Water as Affected by Quantity of Mixing Water and Age

Cement 1. Water Retained in Paste When Dried at 239 Deg. F.

Mixing, water, gal. per sack	Water retained in dried paste in per cent of dry cement. Moist cured until test.								
	1 day	3 days	7 days	14 days	28 days	3 months	6 months	9 months	1 year
3.38	4.1	6.3	8.3	8.8	9.7	10.6	11.0	11.6	12.6
5.08	5.0	7.7	9.8	10.5	11.7	13.0	14.0	14.7	16.2
6.77	5.7	8.6	10.8	11.7	13.0	14.6	15.9	16.8	18.5
8.43	6.2	9.2	11.5	12.6	13.9	15.8	17.0	18.2	19.9
10.20	6.6	9.6	11.9	13.3	14.4	16.7	17.7	19.0	20.8

Table II.—Quantity of Combined Water as Affected by Temperature of Drying

Cement 1. Mixing Water, 60 Per Cent by Weight (6.77 Gal. per Sack). Paste Dried in Air at Temperatures Shown

Temperature of drying, deg. F.	Water retained in dried paste, per cent of dry cement.			
	1 day	7 days	28 days	1 year
122	9.7	15.5	18.9	24.8
194	7.5	12.2	15.0	20.1
212	6.5	11.7	14.1	19.1
239	5.7	10.8	13.0	18.5
302	5.4	10.1	11.8	14.9
392	5.0	8.8	10.5	12.9

Table III.—Quantity of Combined Water as Affected by Different Cements

Cements, All Standard Portland Cements. Mixing Water, 60 Per Cent by Weight of Cement (6.77 Gal. per Sack). Pastes Dried at 239 Deg. F.

Curing period moist	Water retained in dried paste, per cent of dry cement.			
	Cement 1	Cement 2	Cement 3	Cement 4
3 days..........	8.6	8.2	8.5	7.6
7 days..........	10.8	10.8	11.2	9.6
28 days..........	13.0	12.6	13.1	12.1
1 year..........	18.5	16.8	18.4	16.1

III give some data from studies by Raymond Wilson now under way in the Research Laboratory of the Portland Cement Association, showing a possible range in the amount of combined water. The quantities of water retained for the different conditions of test are expressed in percentages of the cement by weight.

In Fig. 1, the quantities of combined water assumed are 12.6, 14.0, 15.0, 16.2 and 17.4 per cent of the weight of the cement for the five mixes from left to right. This increase in combined water with an increase in water-cement ratio is in accordance with the data quoted from Wilson's tests. It can be seen by a study of Tables I, II and III that these allowances for Fig. 1 represent about 28 days moist curing if the basis for fixing the combined water is assumed as dry air at 120 deg. F.

Combined Water and Watertightness.—If Fig. 1 is studied in the light of the foregoing discussion, it will be easy to see how the watertightness of the concrete is so closely related to the quantity of mixing water and the extent of the curing. This is made particularly apparent through the upper diagram, in which each ordinate represents a unit volume of the paste from the corresponding mix in the lower diagram. Comparing the rich mix at the left with the lean mix at the right, it is seen that in the former 36 per cent of the volume of the paste is represented by uncombined water, while in the lean mix the uncombined water is 60 per cent of the volume. The effect of this difference on the watertightness of the paste is even greater than the percentages indicate. The size of the individual pore spaces in which this uncombined water is held also affects the permeability, for the flow of water under pressure is materially impeded by a reduction in size of the channel. The rich mix, therefore, with its 36 per cent of pores distributed through 64 per cent solid paste, will have a decided advantage over the lean mix, with 60 per cent pores distributed through 40 per cent solid paste volume.

The preceding passage is concerned only with the spaces occupied by uncombined water. Air voids and honeycomb,

where they occur, would obviously alter the leakage relations. This shows the need for such consistencies and aggregate proportions as will prevent air voids and honeycomb if watertightness is to be achieved.

Curing. The vital influence of curing on watertightness can also be visualized from the upper diagram of Fig. 1. Suppose, for example, that, by more thorough curing, the quantity of combined water be made twice as large as that indicated. This would give a proportion of pore space to total paste volume of 19 per cent for the rich mix and 46 per cent for the lean. Using the method of comparison of the preceding section it is seen that 19 per cent pores in 81 per cent solid paste will be a much more resistant paste even than the one with 36 per cent pores in 64 per cent solid paste. In the case of the lean mixture also such curing is seen to make an important difference. The 60 per cent pores and 40 per cent solid matter now become 46 per cent pores and 54 per cent solids.

Considerable experimental data are presented showing that this building up of the internal structure of the concrete through the continued hydration of the cement is one of the most effective means of increasing the watertightness.

Minimum Quantity of Cement.—Figure 1 will also be found to show that there is a lower limit to the quantity of cement below which watertight concrete cannot be expected. The diagrams reveal at once that, as the cement quantity decreases from the rich toward the lean mixes, the water-cement ratio necessarily increases so that the proportion of pore space in the paste increases. Since the amount of combined water is evidently related to the quantity of cement, no amount of curing can add enough water to the solid volume of the very lean mixes to overcome this deficiency in cement. Even though a certain aggregate combination may be highly favorable (by requiring less paste than another), the concrete cannot develop a high degree of watertightness unless it contains enough cement to permit an effective building up of the

internal structure through curing. For a guide as to the water-cement ratio permissible, we must look to past experience, together with such additional information as brought out by tests. Later, suitable limits for different classes of work will be indicated.

CHAPTER III

COMPRESSIVE STRENGTH

In the first chapter there was presented a resumé of the basic principles of concrete mixtures in which it was shown how the properties of concrete (plastic concrete) must in the main be dependent on the properties of the hardened cement paste. The properties of the hardened paste, in turn, it was pointed out, were dependent on these three factors:

1. Characteristics of the cement.
2. The proportion of water to cement—the water-cement ratio.
3. Extent to which chemical reactions of hardening are complete.

In the second chapter these last two points were further amplified. In this chapter data are given showing the soundness of these conclusions as regards compressive strength.

Emphasis was placed in the first chapter on the need for a plastic consistency, as the dry, stiff mixes are incapable of proper placement by the usual methods and the thin, watery mixes result in segregation. This precaution is of special importance in the matter of watertightness, but it is also important if the laws of strength developed herein are to apply. All the strength data submitted are limited to those mixtures which are capable of being properly placed and which remain homogeneous when once in the forms.

Water-cement Ratio Strength Relation.—Since Abrams first pointed out the general relationship between quantity of mixing water and compressive strength of concrete there have been many investigations further substantiating his broad conclusions. These further studies have also served to fix more definitely the limits within which the

Abrams' law of strength may be expected to apply and to establish the reasons for such limitations. Figure 2 to 10 show the water-cement ratio strength relation for a wide variety of materials and conditions. These have been specially selected to show the effect of the principal factors which have been found to influence this relationship.

A number of tests have been reported from time to time in which variations in the position of the water-cement ratio strength curves for different materials or conditions have been somewhat greater than indicated in the accompanying figures. In many cases, however, these discrepancies have been due to neglect of certain important factors. One of these is the direct loss of water from the mix through absorption, evaporation or leakage from the forms. Another is the change in character of the mix, due to segregation in the mold. Failure to provide for these properly must naturally affect the results. Still another factor is the use of mixes that are too stiff or harsh to place properly. The importance of this has already been pointed out.

Effect of Size of Aggregate.—For ordinary size ranges, size of aggregate has no appreciable effect on the strength of concrete of a given water-cement ratio. This is shown by Figs. 2, 3 and 4. Fig. 2 shows the results of the tests of concretes in which the maximum size of the aggregate varied from $\frac{1}{4}$ to 3 in. In this the same curve between strength and water quantity fits the data for all sizes of aggregate. Other tests bearing on this factor have been complicated by the effect of size of specimen with respect to size of aggregate particles. The tests in the research laboratory of the Portland Cement Association have shown that when the specimen diameter is less than about four times the maximum particle size there is a falling off in strength. To eliminate this variable, the tests in Fig. 2 were made on specimens up to 12 in. in diameter. This large size necessitated making the tests at 14 days, because of the limited capacity of the testing machine.

In Fig. 2, attention should be directed to the points representing the mortar specimens (sand graded from 0-No. 4). In these specimens considerable water segregated from the mass and collected at the top. This water was carefully drained off and measured and the true water-cement ratio for the remaining water was calculated. It is this corrected water ratio that is plotted.

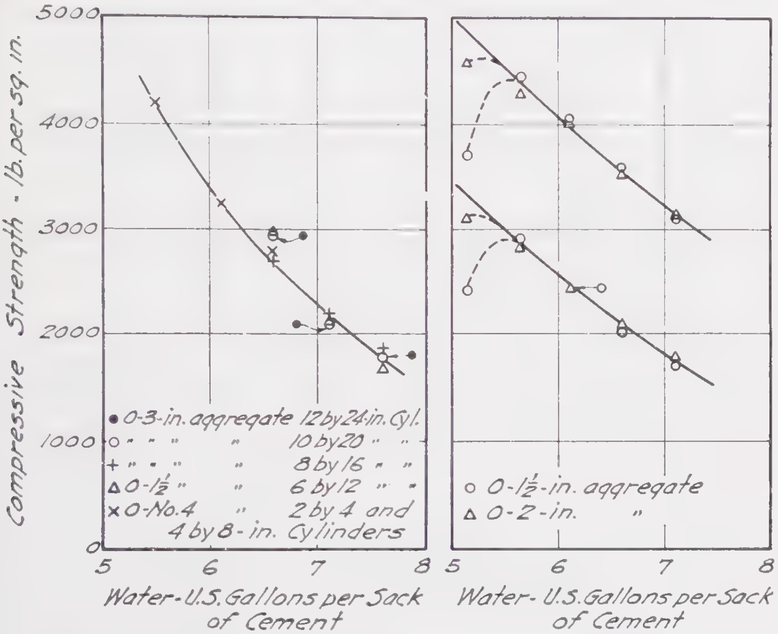

FIG. 2. FIG. 3.

FIGS. 2 and 3.—Effect of size of aggregate on the water-cement ratio strength relation.

In Fig. 2, mix variable; consistency variable; moist cured; age at test 14 days; slump 6 to 10 in. In Fig. 3, mix 1: 2.45: 4 by weight; moist cured; age at test 7 and 28 days.

The perfect continuity in the curve for the three different sizes of aggregate shows the basic character of the water-cement ratio strength relation, when the water ratio is based on the actual water in the concrete as it is finally consolidated in the forms.

Figure 3 shows a comparison of aggregates of $1\frac{1}{2}$ and 2 in. maximum size. The points for the two sizes fall closely along the same curve, indicating that size of aggre-

gate does not influence the position of the water-cement ratio strength curve. This is true for both 7- and 28-day tests. In Fig. 3 can be seen the effect of non-workability on the strength. The dry mixes at the extreme left fall somewhat below the curve. These tests were for a constant mix, so that changes in water content changed the consistency.

Water-cement Pastes. Figure 4 shows the water-cement ratio strength curve for neat cement pastes. These curves

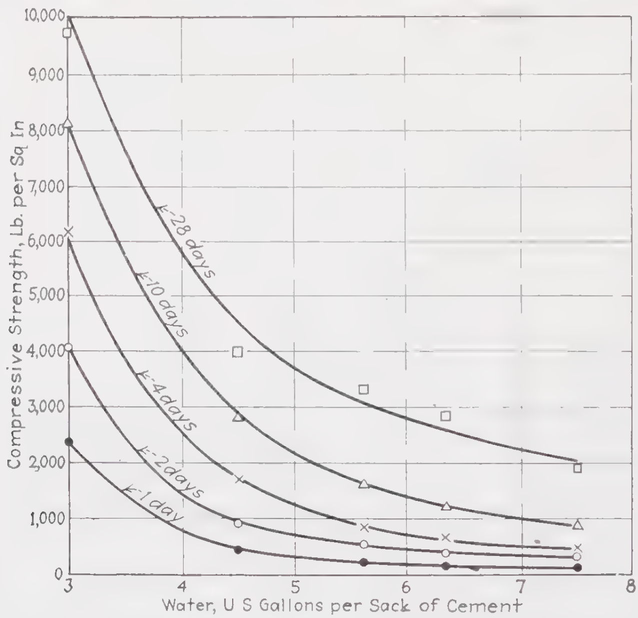

FIG. 4.—Water-cement ratio strength relation for pastes only. Two by four-inch cylinder molds sealed to prevent loss of water; neat cement pastes, moist cured.

are similar in character and position to those for corresponding ages in the other figures presented, showing that whether aggregates are used or not the water-cement ratio governs the strength. In these tests the molds were sealed to prevent leakage. For the wetter mixes there was some accumulation of water at the top of the specimens as in the mortar specimens of Fig. 2. In this series of tests, however, the correction was not made for this amount of

water as the tests were not made primarily for this purpose. The effect of such a correction in the curves of Fig. 4 would be to move the points for the wettest mixes somewhat to the left and the next point or two slightly in the same direction, thus changing the shape of the curves slightly at the higher water ratios.

From the data in Figs. 2 to 4 it is seen that the size of the aggregate is not an important factor in the water-cement ratio strength relation, provided the tests are conducted with due regard for the other variables and the true water-cement ratio of the concrete in place is considered.

Effect of Grading of Aggregate.—The grading of the aggregate has much less effect on the water-cement ratio strength relation than is commonly believed. It is probable that many have failed to recognize this fact due to the common practice of comparing different materials on the basis of certain definite mixes. On this basis, grading does affect the strength because of the difference in amount of water which different gradings require for the same consistency. When these differences in the amount of water are taken into account, that is, when compared on the basis of water-cement ratios, the differences in strength due to grading are not so important. Too often tests have been made in which non-workability or segregation has been ignored. This has also served to emphasize the differences in grading. In Fig. 5, the small effect of grading on the water-cement ratio strength relation is well brought out. This figure shows the maximum range in position of the water-cement ratio curve for very wide differences in grading of aggregates having a maximum size of $1\frac{1}{2}$ in.

The upper curves in Fig. 5 are for coarse aggregates of gravel and the lower curves for limestone. For both coarse aggregates, two separate gradings were used—No. 4-$1\frac{1}{2}$ in. and $\frac{3}{4}$-$1\frac{1}{2}$ in. Sands of two gradings were used in both cases, 0-No. 4 and 0-No. 14. Each sand was combined with each coarse aggregate in a number of ratios ranging from all sand to combinations in which the coarse aggregate proportion was the largest that could be used and obtain

proper placement. Each aggregate combination was used in three mixes, 1:3, 1:5 and 1:7 (cement to mixed aggregate by volume), and each mix was carried through

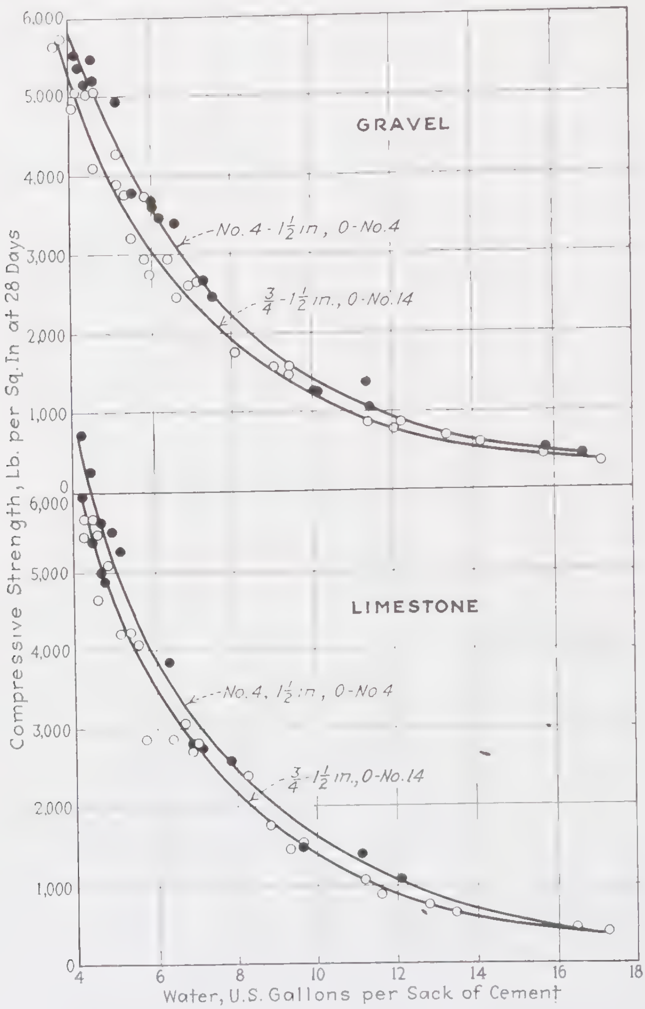

FIG. 5.—Effect of grading on water-cement ratio strength relation. Mix, 1: 3, 1: 5, 1: 7, three consistencies for each mix.

three consistencies. Only workable mixtures have been included in the figure. It will be recognized that for aggregates of this size the range in gradings is quite extensive.

In plotting the data in Fig. 5, only the highest and lowest water-cement ratio curves of the entire set of data are shown for each coarse aggregate. The curves for all the other combinations in both the limestone and gravel concretes fall within the area between the high and low curves shown. It is of interest to note that in both cases the grading showing the lowest position for the water-cement ratio curve is the one with the largest gap in the size distribution. The total range in position of the curves is quite small considering the actual differences in gradings represented.

The real significance of grading of the aggregate is in relation to the workability and economy of concrete mixtures. This is considered in detail in Chapter V.

Effect of Type of Aggregate.—Differences in the water-cement ratio strength relation for aggregates of different types have frequently been brought out. In tests of this factor it is important to take into consideration the differences in absorption between the different materials or else use aggregates which have first been saturated and then brought to the surface-dry condition before using. With this correction the differences between different aggregates ordinarily become of much less importance for the usual range of water-cement ratios.

Figure 6 shows the results of a group of tests in which aggregates of different types were used. For these aggregates the greatest difference is seen to be quite small, and for most of the materials the difference is negligible. Such differences as do exist in the harder materials are more likely to be due to differences in shape and surface characteristics than to strength or mineral structure.

The bond between the cement paste and the aggregate surface is probably one of the most important causes of differences between different types of aggregate. This is affected by the shape and surface characteristics, particularly the angularity and roughness and the amount and character of dust adhering to the surface.

Naturally, materials which are structurally weak or friable cannot be expected to give the same strength as the structurally sound materials. In all the discussions in this book involving strength of concrete it is presumed that only materials satisfactory in these regards will be used. As will be brought out later, the differences between different types of materials are more pronounced in their effect on transverse and tensile strength than on compressive strength, the largest variations occurring for those cases where the bond or tensile strength is low.

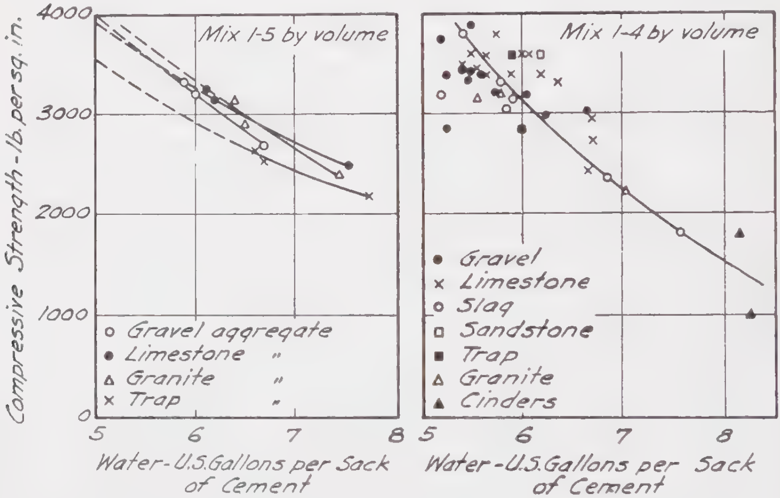

FIG. 6. FIG. 7.

FIGS. 6 and 7.—Effect of type of aggregate on the water-cement ratio strength relation.

Grading variable; moist cured; age at test, 28 days.

Figure 7 shows another group of tests using coarse aggregate of different types, in which a single curve interprets quite well the relation between strength and water-cement ratio for the different materials. In this group of tests there was also some difference in grading, which may be responsible for some of the spread in the points, though probably not a great amount.

Figure 5 which illustrates the effect of grading also provides a comparison of two different coarse aggregates. In this

figure it will be noted that the position of the water-cement ratio curve for the gravel is quite close to that for the limestone for the higher water ratios. For the lower water ratios, however, the strength shown by the limestone for any water ratio exceeds that for the gravel by an amount varying up to a maximum of nearly 1000 lb. per square inch. This may be the result, either of a better bond afforded by the rough angular particles, or of the greater amount of paste in the unit volume of concrete. Other groups of tests with these same materials have shown the same divergence in curves for the lower water ratios, that is, for the richer mixes.

Effect of Curing.—In Chapter II, attention was given to the possibility of building up the internal structure of concrete through continued curing, and some data were presented showing the amount of water that could become a permanent part of the solid mass. The fact that curing increases the strength of concrete is generally recognized, but it is not likely that the full possibilities for improvement through additional curing are widely realized. The data presented here will show something of these possibilities and bring out the minor significance of the other variables discussed when considered in comparison with this major factor.

Figure 8 shows the water-cement ratio strength relation for concrete at the age of 4 months for different periods of moist curing. Comparing the curves for 3 and 21 days moist curing, it will be seen that the extra 18 days in moist sand adds from 1200 to 1800 lb. per square inch to the strength of the concrete at 4 months.

The comparison between the 21 days moist curing and the curing damp for the entire period cannot be fairly made from this figure, as the difference in moisture condition at time of test is involved. The curve representing damp sand storage for the entire 4 months would be still higher if the specimen had been dried before testing. This difference in strength due to moisture condition at time of test is generally recognized.

Figure 9 gives another comparison of the effect of curing. As in Fig. 8, if the moist-cured specimens had been dried before testing, the comparison would have shown a still greater advantage for the moist curing. This would be true for both the 28-day and 1-year tests.

In these curves it is seen also how the two factors of water content and degree of chemical combination are interrelated in the development of strength in the cement paste. In shape, the curves are generally similar to those from the other tests, each degree of curing providing its

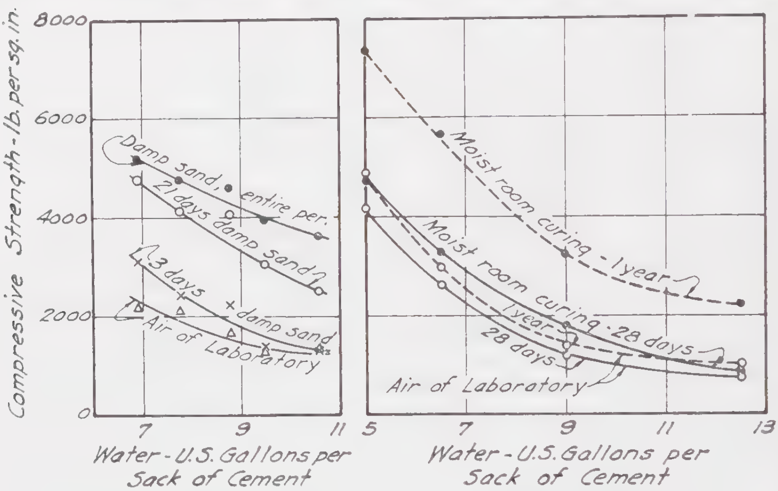

FIG. 8. FIG. 9.

FIGS. 8 and 9.—Effect of curing condition on the water-cement ratio strength relation.

In Fig. 8, mix 1:4 by volume; gravel concrete; age at test, 4 months. In Fig. 9, mix variable, ranging from 1:3½ to 1:9; consistency constant; slump, 3 to 4 in.

own curve. Thus, changing either the water ratio or degree of curing does not alter the importance of the other.

From a study of the data in Figs. 8 and 9 it is seen how important is the matter of curing as compared with the small differences shown for the other variables which have been considered. As will be brought out at other points in this text, *these data show the futility of too fine distinctions in these lesser variables when such important differences are possible through additional moist curing.*

Effect of Age.—It was suggested in Chapter I that age was one of the factors in the curing of concrete. This has also been recognized in the discussions of Figs. 8 and 9. Thus, age and curing cannot be separated; an increase in age merely providing for further chemical combinations if the conditions are favorable for continued reaction. This is illustrated in Fig. 10, which shows the effect of age on the water-cement ratio strength relation for moist-cured concrete. There are two points of special interest concerning the curves in this figure. First, the similarity in the curves representing the water-cement ratio strength

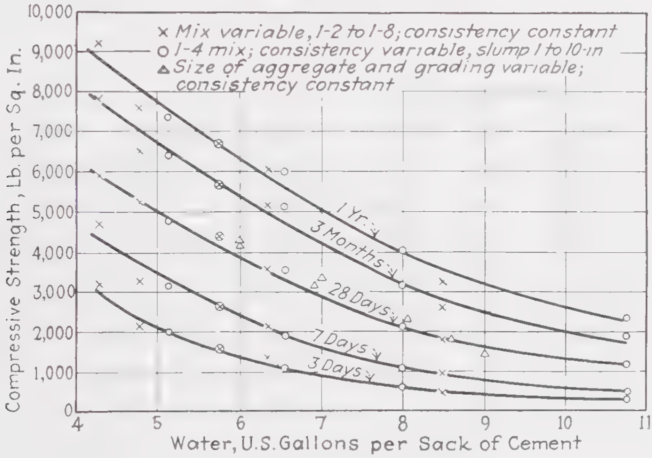

FIG. 10.—Effect of age on the water-cement ratio strength relation. Moist room curing.

relation for the various ages; and second, the significance of variations in mix, consistency, size of aggregate, and grading. On this latter point it will be noted that for each age the water-cement ratio fixes the strength, regardless of the cement content, consistency, or aggregate characteristics. This point, which has been brought out in the discussions of the other figures, emphasizes the fundamental character of the water-cement ratio strength law.

The similarity of the curves for different ages is significant in reference to the comment frequently made that the mixes of high water ratio eventually gain strength

more rapidly than the mixes with the lower water content. That this is not the case can be seen from the fact that these curves continue to diverge as the water-cement ratio is reduced.

Effect of Character of the Cement. Of an importance comparable with differences in curing is the effect of the characteristics of the cement on the water-cement ratio strength relation. While all cements behave similarly, they do not all gain their strength at the same rate. This is clearly brought out in Fig. 11, which shows tests of concrete made from 32 brands of cement which were

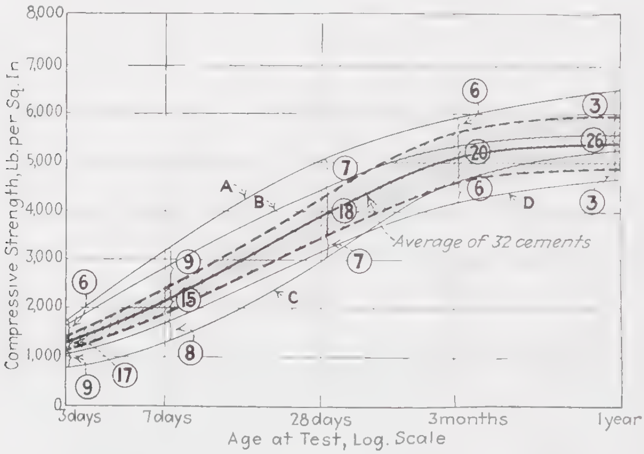

FIG. 11.—Age-strength relation for 32 cements.
Mix 1:2.4:3.6 by weight; water-cement ratio 6.2 gal. per sack; cured in moist room.

studied by committee C-1 of the American Society for Testing Materials and reported at the meeting of the society in 1928 (*Proceedings*, A. S. T. M., Vol. 28, P. 261, 1928). These curves are based on the tests made in the Portland Cement Association laboratory, which was one of the 47 participating laboratories. In this diagram, which represents age-strength relation, are shown two of the highest, two of the lowest and the average of the 32. The shaded area represents a belt 10 per cent above and 10 per cent below the average curve. The numbers in the circles at each of the five ages—3, 7 and 28

days, 3 months and 1 year—represent the number of cements which fall within the band 10 per cent above or below the average, also the number which fall outside of that band on both sides. This method of plotting has been adopted to avoid the confusion from 32 separate curves.

Some of the curves representing individual cements cross from one belt into another, as in the case of cements *B* and *C*: others are more or less parallel with the average, as with *A* and *D*. The increase, as the age at test increases, in the number of cements which lie within the inner belt shows a general tendency toward the *B* or *C* type of curve. This indicates that the difference between cements is more a matter of the rate of gain in strength at the different periods than of the potential strength. This group of 32 cements can probably be taken as representative of the American product, as every section of the country was represented in the selection of the samples to be tested. These samples were purchased from dealers in the open market and it is possible that strengths may have been lowered somewhat in the case of some samples by long storage, no attempt having been made to determine the date of manufacture.

In view of the differences in rate of gain in strength, which are greatest at the early ages, it is to be expected that the water-cement ratio strength curves for different cements at 28 days would differ in position. With a given cement, however, the water-cement ratio curve follows the trend of the curves in Figs. 2 to 10, so that the principals of proportioning mixtures are the same, regardless of the characteristics of the cement.

Effect of Quantity of Cement.—So far only slight comment has been made regarding the mix or quantity of cement. It has been quite clearly brought out in other discussions of the water-cement ratio strength relation that the quantity of cement and the water ratio are inter-dependent factors, a change in the mix being reflected in the strength through the change in water ratio. It is only necessary to emphasize the point here because a clear appreciation of this inter-

dependence is essential to an understanding of the principles of proportioning. The fact that the relation of strength to water ratio remains constant over a wide range, in which both the consistency and mix are varied, shows that for given materials and conditions of curing it is not the amount of cement in the mix but the proportion of cement and water that determines the strength. Figures 5 and 10 are typical of many tests which show how the quantity of cement affects the strength only as it affects the quantity of water necessary to give the required consistency.

CHAPTER IV

WATERTIGHTNESS AND OTHER PROPERTIES

In Chapter III, data were presented showing that the compressive strength of concrete is determined largely by the three factors given in the resumé of Chapter I. In this chapter, experimental data are presented showing that the same three factors largely determine the watertightness and other properties of concrete.

The need for a plastic consistency in placing has been repeatedly pointed out. This is of paramount importance where watertight concrete is required. If the concrete is so placed that the entire space between the aggregate particles is not filled with the paste, watertightness cannot be expected regardless of the quality of the hardened paste. Likewise, if the consistency of the mixture is such that segregation occurs, either in placing, or through settlement after placing, differences in watertightness in various parts of the structure will exist due to this unbalancing of the mixture.

Unfortunately, experimental data on the permeability of concrete have been rather limited in the past and many of those available cannot be analyzed in a manner that shows the relation between watertightness and the primary factors mentioned above. In the two most important series of older tests, those at the University of Wisconsin and a the Department of Industrial and Scientific Research, London, an opportunity is given to study permeability in relation to water-cement ratio and extent of curing. Abstracts from these are given herein. In a series of tests now under way at the Research Laboratory of the Portland Cement Association by Inge Lyse and the author, these important variables are being studied in a systematic way. Some of the results of these tests are now available and are given below.

Earlier Tests of Permeability

University of Wisconsin Tests. One of the most exhaustive series of tests of permeability is that made at the University of Wisconsin by Withey and Wiepking. (See

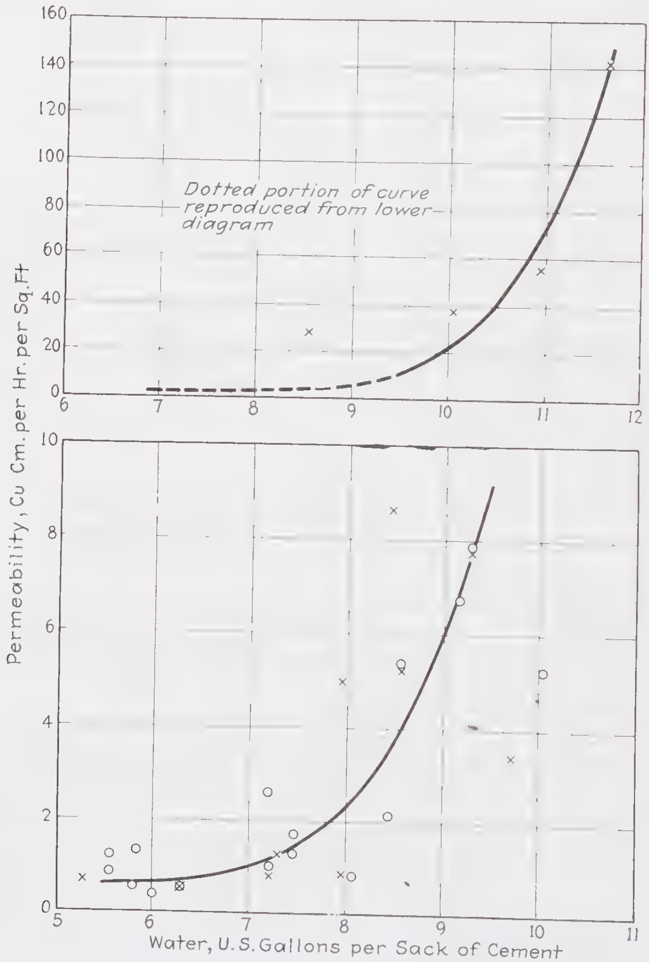

Fig. 12.—Permeability of concrete (University of Wisconsin tests). Variable mix and consistency; damp cured; age at test, 28 days.

Bull. **1245,** Permeability Tests on Broken Stone Concrete, by Withey and Wiepking, University of Wisconsin, Engineering Series, Vol. 19, No. 2.) In this series, variations

in the water-cement ratio were not studied as such, but certain of the data provide an opportunity for comparison on this basis. Thus, two sets of data in Withey and Wiepking's paper—those in Table VIII, in which the water-cement ratio and consistency are variable, and those in Table VI, in which the water-cement ratio and mix are variable—can be grouped in a single study with the water-cement ratio as the basis of comparison. This has been done in Fig. 12. This figure shows the relation between the water-cement ratio and the average rate of loss of water through the specimen for the first 50 hours under test at 40 lb. per square inch pressure. In order to enlarge the scale for the lower values, the data have been plotted in the two sections. The dotted portion of the curve in the upper diagram is a reproduction to different scale of the curve in the lower diagram.

One feature of these tests, upon which the authors commented and which is apparent when these data are compared with other data on permeability, is the very small quantities represented by the losses shown. Many of the specimens, the authors state, did not show any dampness on the surface during test, indicating that evaporation from the surface was at least as rapid as the flow through the specimen. The quantities of water reported as leakage were determined by measuring the quantity that went into the specimen. Because of the small quantities involved, the results would be influenced by other factors than simple permeability of the pastes, such as rate of evaporation, humidity, etc.

While the points in Fig. 12 are scattered somewhat, the general trend, showing increase in leakage with increased water-cement ratio, is well defined. When the difficulties of making such tests are considered, it will be appreciated that this is a very satisfactory indication of the major influence of water content of the paste on the watertightness of concrete.

In the conclusions from their studies, Withey and Wiepking point out the importance of curing as follows:

To secure a high degree of imperviousness, concrete should be cured in a moist atmosphere or under water. At temperatures of 60 to 75 deg. F., the moist-curing period should be maintained for 2 weeks to a month after molding. Lean mixes or thin sections require longer wet-curing periods than rich mixes or thick sections. When it is impracticable to keep the work moist after removal of the molds, and the humidity is low, provision should be made to keep the molds in place in order to avoid evaporation. The effect of dry curing appears to be much more detrimental to watertightness than to compressive strength.

Tests by Department of Industrial and Scientific Research.—Figure 13, taken from Fig. 4 of Building Research Paper No. 3, Department of Industrial and Scientific Research, London, gives some further data showing the relation between permeability and the quantity of mixing water. Here the regularity of the curves will be noted, showing the important effect of the water-cement ratio. At 28 days, the use of 8.3 gal. gave a leakage more than 3 times that obtained with $6\frac{3}{4}$ gal. For the 7- and 14-day tests the difference was even greater. The upward trend at the lower water ratios is deserving of comment, as it shows the importance of proper consistency. This group of tests being on a fixed mix (1:2:4 by weight), the mixtures would naturally become stiff for the lower water contents, with the result that the permeability would increase due to the difficulty of obtaining proper placement.

These tests also show the importance of curing on the watertightness.

In Fig. 13 the separate curves for 7-, 14- and 28-day tests are in a measure a direct comparison of differences in curing. As pointed out in the discussion of strength data, curing and age are not separable, the only effect of age on the strength being the opportunity it provides for further chemical union between the cement and water. This must be true also in the effect on permeability. Thus, the 14 or 7 days moist curing in Fig, 13 might be equivalent to

28 days curing under less favorable conditions. The curves of Fig. 13 clearly show the importance of the completeness of the chemical combinations on the resistance to the

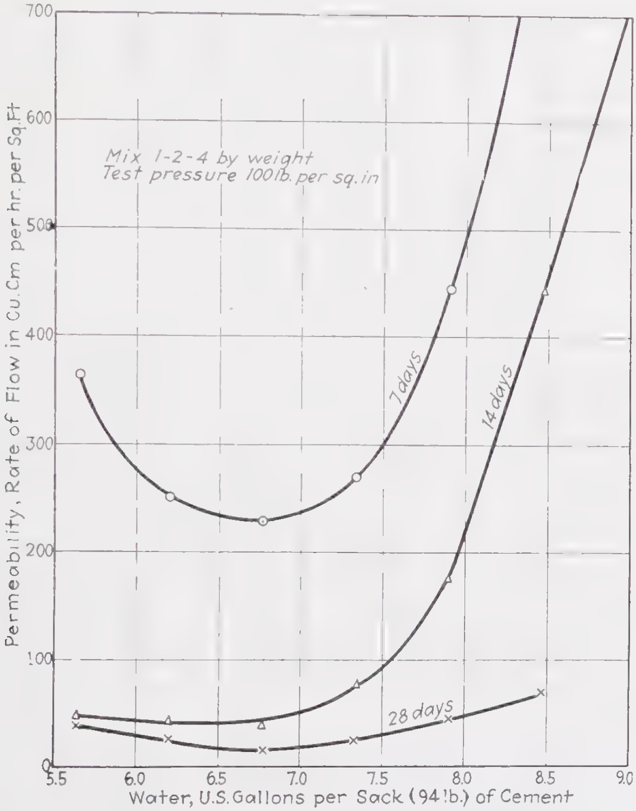

FIG. 13.—Permeability of concrete (London tests). Constant mix; variable consistency.

passage of water. The leakage after only 7 days curing is four times that obtained at 14 days, and eight times that at 28 days.

Permeability Tests at the Research Laboratory of the Portland Cement Association

Figures 14 and 15 show the results of tests at the Research Laboratory of the Portland Cement Association. These

cover the three factors of water-cement ratio, curing, and characteristics of cement, also the effect of admixtures.

Effect of Water-cement Ratio and Curing.—In all the diagrams of Figs. 14 and 15 the important influence of the water content of the paste will be noted. Both the effect of additional moist curing and the water-cement ratio are brought out particularly well in Fig. 15. In the upper diagram of this figure a separate curve is shown for three mixes of different water-cement ratios for each of which the important effect of longer curing is clearly seen. In the lower diagram, both the water-cement ratio and the curing are again seen to be the important factors regardless of which cement is used.

These data, as pointed out above, are not so extensive as those bearing on the water-ratio strength relation. Nevertheless, when considered in connection with the latter there can be no escaping the conclusion that as in the case of strength, *the water content of the paste and the degree of curing are the major factors affecting watertightness.*

In this connection should be mentioned the tests by H. F. Faulkner and F. D. Crook, Seattle, reported in the paper "Tests of Damp Sand Curing Improves Quality of Concrete" (*Engineering News-Record*, June 19, 1924 p. 1050) which brought out most surprisingly the effect of additional curing on the resistance of concrete to the absorption of oils.

Effect of Admixtures.—The upper diagram of Fig. 14 shows the effect of admixtures on the watertightness of concrete of different mixes tested at the age of 28 days after 7 days moist curing. In all cases where any differences were noted the mixes containing the admixtures were the less watertight. This is explainable by the fact that in all cases the use of these admixtures required the use of extra water to maintain the same consistency (slump 3 to 5 in. in these tests).

Many have formed the impression that admixtures are void fillers and, therefore, must in some measure reduce the permeability. These tests, as well as other data, show

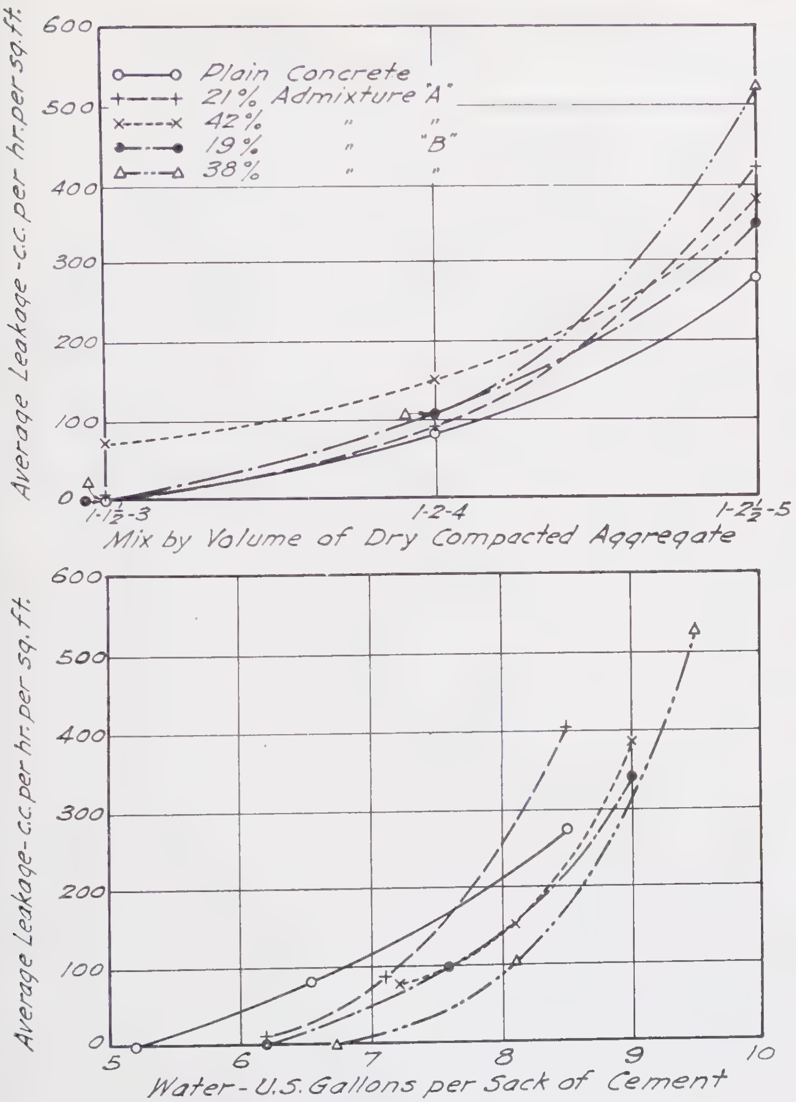

FIG. 14.—Effect of admixtures on permeability of concrete.

Age at beginning of test, 28 days; 7 days moist cured, 21 days in air of laboratory. Six by two-inch cast discs. Pressure, 80 lb. per square inch for 48 hours.

that these finely powdered materials do not have any different relation to the concrete mass than do the fine particles of aggregate or the cement. They merely occupy space in the mass and, therefore, increase the bulk by exactly the amount of their absolute volume. In plastic mixtures all the space not occupied by solid matter is occupied by water; therefore, the addition of extra material increases the bulk whether or not extra water is required to maintain plasticity. Where extra water is required to maintain the consistency some reduction in watertightness is to be expected.

In the lower diagram of Fig. 14, the same data, as from the upper diagram, are replotted using the water-cement ratio as abscissas. When analyzed on this basis it is seen that the leakage for a given water-cement ratio is less when admixtures are used, showing that these admixtures have the capacity of holding within the mass some of the extra water which was required by their use. That this capacity to hold water is not sufficient to maintain the same watertightness is shown by the upper diagram.

Effect of Characteristics of the Cement. Here again the experimental data are limited. On the lower diagram of Fig. 15 are plotted the only data available which show the difference in permeability between cements of different characteristics. These data show the average leakage per hour for 48 hours through 1-in. disks under a pressure of 20 lb. per square inch. The specimens were mortar mixes of constant consistency (slumps from 3 to 5 in.), the mix being adjusted to give water-cement ratios of 5, 6, 7 and 8 gal. per sack of cement. Two groups of specimens are shown—those cured moist for 3 days, followed by 7 days in the open air, and those cured moist for the entire 10 days; all specimens were tested at 10 days.

Cements *B* and *D* are standard portland cements; cements *A* and *C* are special cements now on the market. While the data shows some differences among the different cements, it is only in the case of Cement *C* that the difference is prominent enough to be of any important

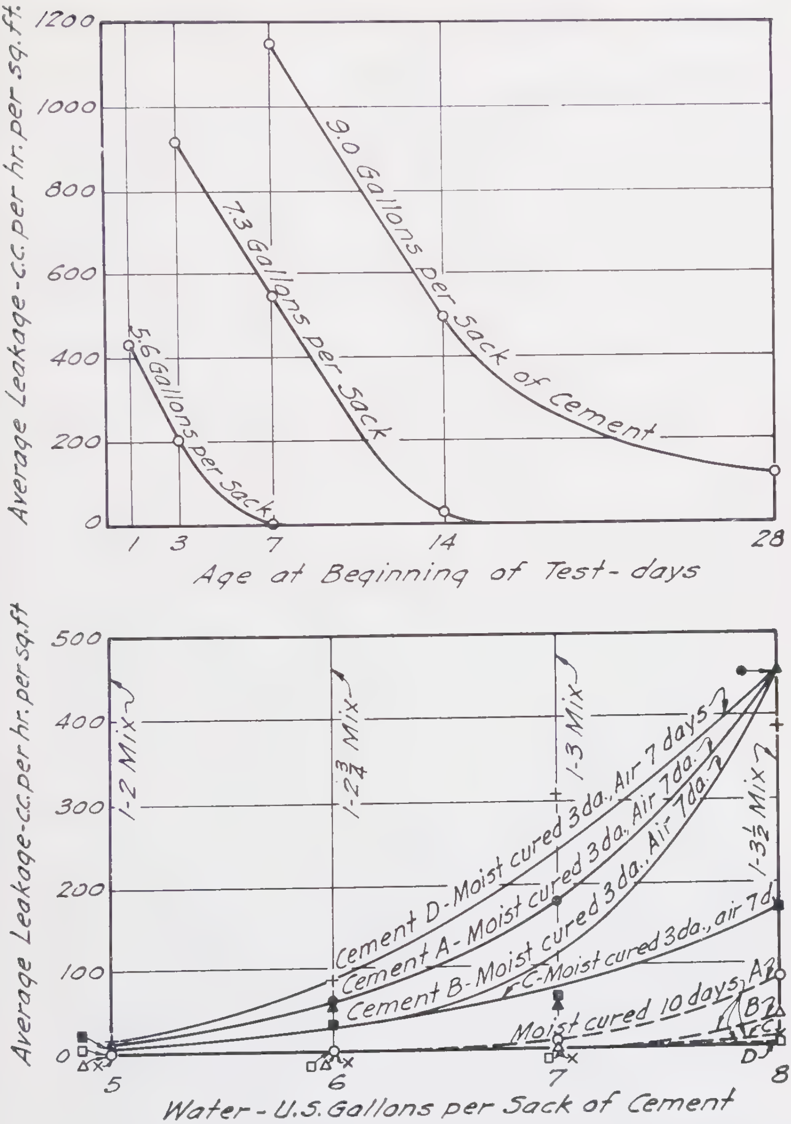

FIG. 15.—Effect of water content and curing on the permeability of concrete. Six by one-inch cast discs. Pressure, 20 lb. per square inch for 48 hours.

consideration, and this is true only for the highest water-cement ratio.

As compared with the differences between the various cements, the differences due to water ratio and to curing should be carefully noted. For example, the leakage for the cement lowest in position for the 7-gal. water ratio is about as great as that for the highest cement for the 6-gal. water ratio. Of still greater significance, however, is the matter of curing. The cement showing the highest leakage for the 8-gal. water ratio, when moist cured for an additional 7 days before test, shows a leakage of less than half that shown by the best cement for the 3 days' moist curing.

Durability and Other Properties of Concrete

Durability.—At the present time there is no direct test for durability of concrete. Experience has shown, however, that of all the destructive agents, freezing of absorbed moisture is the most severe. For this reason freezing and thawing tests are regarded as the best measure of durability at the present time. Unfortunately, the number of tests of this kind is very limited, but such as are available indicate that the same laws which govern the strength of concrete also govern its resistance to the weathering effects of freezing.

In a paper entitled "Some Accelerated Freezing and Thawing Tests on Concrete," by C. H. Scholer, presented before the American Society for Testing Materials in June, 1928, (*Proceedings*, A.S.T.M., Vol. 28, Part 2, p. 472, 1928) there are some very interesting data showing the relation between the water-cement ratio and the resistance of concrete to destructive effects of alternate freezing and thawing. Figure 16, which is reproduced from Fig. 7 of this paper, shows the relation between strength and water-cement ratio and number of cycles required to disintegrate completely the specimens in the freezing and thawing test. In commenting on these data Professor Scholer points out that for the higher water ratios

the specimens failed distinctly by mortar disintegration, while "for the lower water ratios the disintegration of the

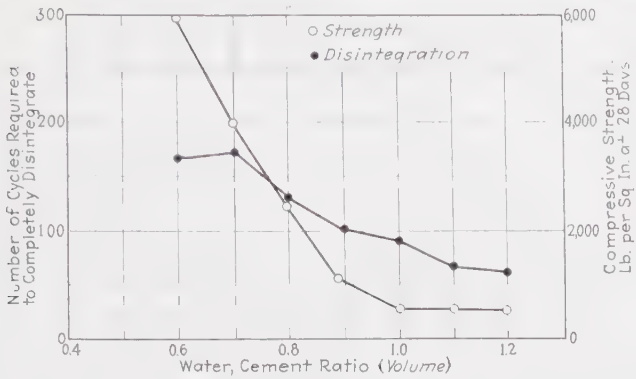

FIG. 16.—Tests on 3 by 8-in. cores cut from 1:2:3½ concrete having variable water-cement ratio.

Frozen at −15 to −25 deg. F.; thawed at 70 deg. F. (Paper by C. H. Scholer, *Proceedings*, A.S.T.M., 1928).

FIG. 17.—Effect of water-cement ratio on durability of concrete.

Showing the effect of 30 cycles of freezing and thawing on concrete of different water-cement ratios. Specimens 28 days old when first frozen. Total age 205 days.

stone is playing a very important part. In fact, most if not all of the failure in the specimen of 0.6 water-cement

ratio appears to have been due to the failure of the coarse aggregate." From this statement it is evident that if the curve on Fig. 16, representing the relation between cycles and water-cement ratio, could be made to represent only the resistance of the paste, it would resemble still more closely the curve between strength and water-cement ratio.

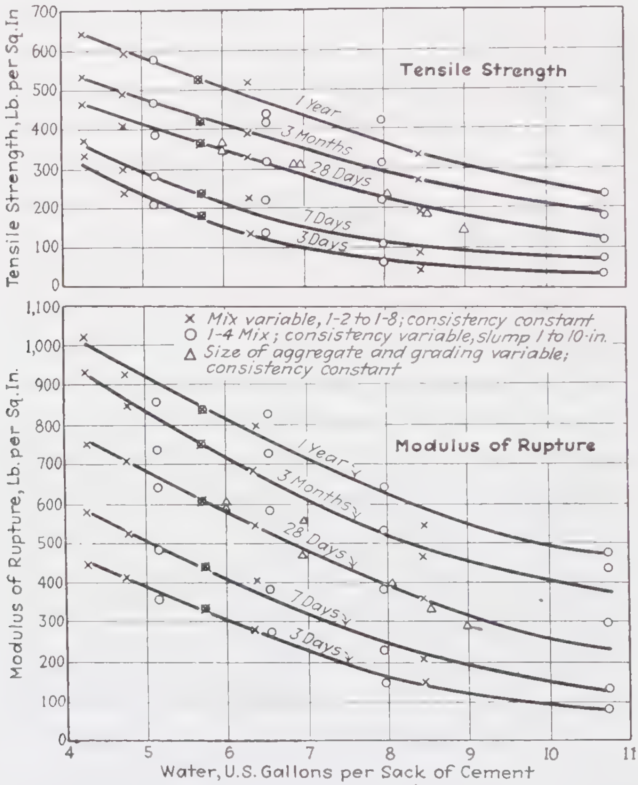

FIG. 18.—Effect of water-cement ratio on the tensile and transverse strength of concrete.
Moist room curing.

In Fig. 17 are shown some results from freezing and thawing tests now under way at the Research Laboratory of the Portland Cement Association. This is a picture of specimens after 30 cycles of freezing and thawing. As can be seen from the picture the specimens with the

water-cement ratio of $7\frac{1}{2}$ gal. per sack are still in excellent condition at this stage of the tests, while those with a water-cement ratio of 9 gal. have begun to show pronounced effect of the expansive force of the freezing water in the pores. These specimens are typical of many others in these tests in which the resistance is shown to depend on the water content of the cement paste. The effect of curing is being studied also, but the data bearing on this factor are not available at this time.

Transverse and Tensile Strength.— In Fig. 18 are shown the results of transverse and tensile tests of concrete at various ages plotted in terms of the water-cement ratio. The upper group of curves represents the tensile strength and the lower group the modulus of rupture. The same characteristics of the water-cement ratio strength relation will be noted in this group as found for the compressive strength shown previously. Other tests have shown that the characteristics of the aggregates affect the transverse strength to a greater degree than the compressive strength. The important effect of curing can also be seen from Fig. 18 by the increase in strength with age as indicated by the separate curves. These data are taken from a paper by Gonnerman and Shuman, entitled Compression, Flexure and Tension Tests of Plain Concrete, (Proc. Am. Soc. Testing Mat. vol. 28, Part 2, p. 527, 1928).

CHAPTER V

COMBINING AGGREGATES WITH CEMENT PASTE

In the preceding chapters it has been demonstrated that for *plastic mixtures* (to re-emphasize, a plastic mixture is one in which all the space between aggregate particles is thoroughly filled with cement-water paste) the properties of the concrete are principally determined by the properties of the hardened paste. It has also been shown that the properties of the hardened paste can be completely controlled through the relative proportions of cement and water and the degree of curing attained. Proportioning concrete for a given purpose, therefore, consists in the two steps already pointed out:

First, to select such proportions of water and cement and such conditions of curing as will produce a paste to meet the requirements for the particular structure as to strength and watertightness.

Second, to find that combination of aggregates and paste which will produce a plastic mixture that will remain homogeneous during placing and after it is in place.

It is with the second step of this method of proportioning concrete that this and the following chapter are concerned. In this chapter consideration will be given to the factors influencing the relative quantities of aggregate and paste and the proportions of fine to coarse aggregate which are necessary to give a plasticity that will meet the requirements of handling and placing. It will be shown that no elaborate theories or calculations are required to arrive at suitable proportions but rather that the desired results can be attained by a few simple trials and the exercise of judgment.

The following chapter will be devoted to a more detailed discussion of the method of designing concrete by trial mixtures and a presentation of helpful data for its use.

Many have found difficulty in translating the results of their study and experience with concrete, on the basis of fixed proportions of cement and aggregate, to the basis of this new method where the quality of the paste is fixed by the water-cement ratio, leaving the aggregate proportions as a secondary consideration. Once this difficulty is overcome, it will be found that the method is not only easy to grasp but exceedingly helpful in explaining many things that were known to be true only through experience. It is believed that the discussion of this chapter will help materially to clarify these points.

Grading of Aggregates

Significance of Grading and Density.—The grading of aggregates has occupied a very prominent place in the literature of concrete. This is eminently right and proper when thinking in terms of certain definite mixes, for with a fixed quantity of aggregate per unit of cement the grading is a major factor in strength and other desirable qualities. That this is true can be seen in the curves of Fig. 19, where in the upper left-hand drawing are shown the strengths plotted in terms of the density from a group of concretes of three different mixes based on a rather wide range of combinations of fine and coarse aggregates of different gradings. Density, as the term is used here, is the ratio of the sum of the absolute volumes of cement and aggregate to the volume of the concrete. The different densities in these tests resulted from the different gradings.

An inspection of these upper left-hand curves in Fig. 19 shows a fairly regular relation between compressive strength and density for a particular mix, there being a separate curve for each of the three mixes. It is seen that the compressive strength for any mix decreases as the density decreases; for example, with the 1:5 mix (one sack of cement to 5 cu. ft. of mixed aggregate), a change in grading which reduces the density from 0.85 to 0.75 reduces the strength by more than half. This change in strength is not due,

as is so apt to be thought, to the change in grading as such, but results from the difference in water required to maintain the given consistency. The difference in water required is brought out by the lower curves in Fig. 19, where the same data are plotted, but on the basis of density against water-cement ratio. In this lower diagram each mix and consistency gives a separate relation between density and water quantity, showing that density is not a measure of concrete quality that can be universally applied. Density

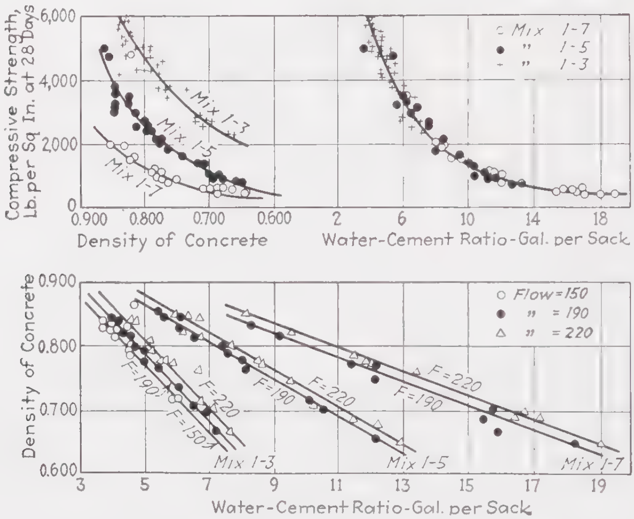

FIG. 19.—Density, strength and water-cement ratio. 0 to No. 4 sand and No. 4 to 1½-in. gravel.

is a measure of quality only when the mix and consistency remain unchanged, since it is only for these conditions that it is an accurate measure of water required.

Before leaving the matter of density the curve at the upper right should be studied. In this, the same data are again plotted, but this time as strength against water-cement ratio. Here it is seen that all of the mixes and consistencies, which required separate curves in the two other diagrams, are interpreted by a single curve—showing the universal character of the water-cement ratio law.

Grading as an Economic Factor.—To bring out more fully the significance of grading under the two different methods of proportioning—by fixed mixes or for a given quality of paste—Table IV has been prepared. In this table are three mixes from the group of tests forming the basis of Fig. 19, selected to show an extreme range in grading in order to bring out the factor of economy more clearly; it is not likely that such a range in grading would ordinarily be encountered in the materials available for a single job. The first two mixes in the table furnish a comparison on the basis of arbitrary proportions (1:5 mix), and the first and third a comparison on the basis of like quality of paste. The latter comparison is approximately fair but is not quite exact, as the water-cement ratio for the third mix is a half-gallon lower than for the first, with a correspondingly higher strength, due to the fact

TABLE IV.—COMPARISON OF MIXES

Mix by dry volume		Aggregates used		Water-cement ratio, gal. per sack	Slump, in.	Density of concrete	Cement, sacks per cubic yard	Cost*	Compressive strength 28 days, lb. per square inch
Mixed aggregate	Separated aggregate	Fine	Coarse						
1:5	1:1.95:3.80	0–No. 4	No. 4–$1\frac{1}{2}$ in.	6.0	3.0	0.85	5.4	$6.66	3,600
1:5	1:3.46:2.60	0–No. 14	$\frac{3}{4}$–$1\frac{1}{2}$ in.	9.5	3.3	0.75	4.8	6.05	1,600
1:3	1:2.07:1.55	0–No. 14	$\frac{3}{4}$–$1\frac{1}{2}$ in.	5.5	2.5	0.76	7.5	7.77	3,800

* Cost per cubic yard of concrete for materials only. Cement at $2.80 per barrel; sand and gravel at $2.50 per cubic yard.

that there were no mixes between the 1:5 and 1:3. A mix of 1:3½ would have given about the same water-cement ratio and strength.

In the first mix in Table IV the aggregate is a good combination containing 36 per cent coarse sand and 64 per cent graded coarse aggregate, whereas in the second and third mixes the aggregate contains 59 per cent fine sand and 41 per cent coarse aggregate of almost no range of sizes. In comparing the two 1:5 mixes it is seen that because of this difference in grading it was necessary to increase the water content 3½ gal. per sack in order to maintain a plastic consistency; the increase in water content resulted in a reduction in strength of 2,000 lb. per square inch with only 10 per cent reduction in cost. On the other hand, by comparing the first and third mixes it is seen that, with the quality of the paste fixed (definite water ratio), the desired strength is readily obtained with the unfavorable grading, though at an increased cost.

Application to Design of Mixtures.—The point it is desired to emphasize by the foregoing illustration is that when proportioning concrete for a definite quality through fixing the water content of the paste, the grading of the aggregates becomes principally a question of economy and workability. In this illustration it is seen that an extraordinary range of gradings, which in 1:5 mixes reduces the strength more than half, represents only a matter of 16 per cent increase in cost when compared on the basis of concrete of constant strength. It can be shown from the figures in the table that the sand and the well-graded coarse aggregate of the first mix could each carry an extra cost of $1 per cubic yard before it would be more economical to use the materials in the third mix at the prices assumed.

If the illustration of Table IV with its extreme range in grading is carefully studied, it will be apparent that intermediate combinations of aggregates would show intermediate results as to mixes and cost. From such a study it can be realized that many possible combinations which give low strengths when compared with the first mix on

the basis of 1:5 concrete might give favorable costs when compared on the basis of equal strength by using a paste of the required quality—that is, the extra quantity of paste might easily be offset in cost by favorable combinations of cheaper aggregates.

Comparison of Ordinary Gradings. Supplementing the foregoing illustration, it is of interest to compare a number of mixes in which the grading varies within the range ordinarily encountered in concrete materials. Such a comparison is offered by Fig. 20, which shows four groups of mixes in which the quality of the paste in each group is fixed by a constant water-cement ratio, while the grading is varied by changing the ratio of fine to coarse aggregate. In these mixes the sand and gravel were of good grading, and the combinations with the paste were such as to give a constant slump of 6 in. for all water ratios. It will be noted that the mixes for each group vary from an all-sand mix to one in which the amount of coarse aggregate is at or beyond the probable limit of workability.

These mixes are plotted in the lower diagram of Fig. 20 in the manner used in Fig. 1 of chapter II in which the ordinates represent one unit volume of concrete divided to show the absolute volume occupied by each of the ingredients. In this diagram the fine and coarse aggregates are shown separated.

In order to make the similarity with Fig. 1 complete, an amount of combined water has been assumed which bears the same ratio to the amount of cement as used in Fig. 1 for similar water-cement ratios. As in Fig. 1 also, air voids have been ignored. These would be about 3 per cent for the all-sand mixes and less than 1 per cent for the other mixes. In the upper diagram are plotted the costs for the materials in 1 cu. yd. concrete for each of the mixes in the lower diagram.

The differences in grading in Fig. 20 can be compared by the ordinates representing the total amount of aggregate in the unit volume of concrete. Except for the all-sand mixes it can be seen that quite a variation in the propor-

tions of fine and coarse aggregates results in only a small change in density—that is, in the total absolute volume of solids in the concrete. More significant still is the small difference in cost between those mixes for each water-cement ratio which lie within the range of what would likely be used. Of course, the cost comparison would vary with each combination of prices assumed, but

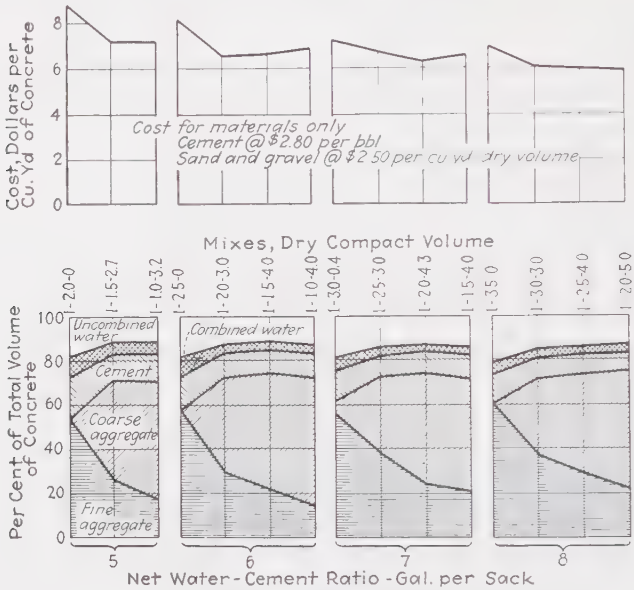

Fig. 20.—Comparison of mixes for constant consistency.

Coarse aggregate: No. 4—1½-in.; weight, 108 lb. per cubic foot dry compact volume. Fine aggregate: O—No. 4; weight 114 lb. per cubic foot dry compact volume. All mixes for slump of 6 in.

it can be seen from the analysis in Fig. 20 that, when designing mixes on the basis of the quality of the paste, considerable latitude is presented for varying the proportion of fine to coarse to take advantage of the existing price schedule. This is the big advantage of such a method of design. It makes possible the best utilization of available materials and at the same time insures the desired quality.

Grading as a Factor in Workability.—In the preceding paragraphs it was pointed out that, when designing con-

crete mixtures on the basis of a definite water-cement ratio, grading of the aggregates becomes principally a question of economy and workability. In the discussion of economy proper workability was assumed—in fact, the limit of workability was made one of the limits of economy. Elsewhere in this text emphasis has been placed on matters of placing, and the need for plastic and homogeneous mixtures has been stressed, particularly where the concrete must be watertight. In selecting the individual aggregates to use, and the proportion of fine to coarse, the requirements of placing and the prevention of segregation must receive first consideration.

With a given set of materials, the best method of arriving at the proper consistency is by trial, using the fine and coarse aggregates in different proportions with a paste of the required water-cement ratio. These trial batches should be observed for placeability and segregation. Mixtures too high in coarse aggregate will place with difficulty, and in the wetter mixes will tend to increase segregation. On the other hand, mixes with a high proportion of fine aggregate place more easily and (unless the sand is very coarse) do not tend to segregate. In the case of very coarse sands there may be a tendency to separation of the paste from the aggregate mass which is not overcome by increasing the sand proportion. Such separation can be prevented only by adding fines to the aggregate or by stiffening the paste through the use of a lower water-cement ratio.

Segregation in Placing.—One of the most serious types of segregation is that which occurs during placing and after the concrete is in place, due to the use of too wet a mixture. As pointed out in the first Chapter in the discussion of overwet mixes, such segregation results in the accumulation of water at the surface as the placing progresses, causing laitance layers and porous concrete immediately below. When these fluid mixes are used, the water-cement ratio of the mass will vary from bottom to top, with consequent differences in strength and watertightness in the

various layers. The remedy lies in control of the plasticity through the grading and proportions of aggregates.

Limiting Factors in Aggregate Proportions

From the study of Fig. 20 it was seen that a considerable range exists in the proportions of aggregates which can be used with a given cement paste without greatly affecting either the density of the concrete or the cost. For the unit prices assumed, it can be seen that cost alone would act as a deterrent to the use of mixes too high in fine material. In the other direction, the matter of workability would act to limit the use of too high a proportion of coarse aggregate. With intelligent supervision, under conditions where costs approximating those assumed prevailed, it would be safe to leave the matter of selection of proportions to be adjusted to meet best the conditions of placement. Under these conditions there would be a tendency to work always toward the most economical mix that is, in the direction of increased amount of coarse aggregate. In this there would be little danger of going beyond the point where the saving in materials was offset by the additional cost of placing the harsher-working mixes.

Sand Limits.—There may be conditions, however, where the relative cost of the fine and coarse aggregate and the cement would be such that economy would tend toward the use of practically all fine aggregate, a result not generally desirable, as brought out later. To avoid such a contingency, some limitations to the proportion of fine aggregate in the mix can be established where it is considered necessary.

A desirable upper limit for the size of aggregates used in the concrete shown in Fig. 20 (sand graded from 0 to the No. 4 sieve and gravel graded from the No. 4 sieve to $1\frac{1}{2}$ in. size) would be that the sand should not exceed the coarse aggregate in amount. For aggregates of less than $1\frac{1}{2}$ in. maximum size, the upper limit to the proportion of sand would need to be increased. For aggregates $\frac{3}{4}$ in. or less in maximum size, the sand content can fre-

quently be considerably greater than the coarse aggregate. The grading of the aggregates and the richness of the mix affect the limits which it is desirable to fix as the maximum sand content.

In the other direction (minimum quantity of fine aggregate) the limits are more easily fixed by the requirements of placing. Too much coarse aggregate renders the mix harsh and difficult to work and tends to increase segregation; these are deficiencies easily recognized and, because of the difficulty of placing, will generally be avoided where opportunity is presented for altering the proportion of fine and coarse aggregates. Generally, harsh mixes on the job are the result of arbitrary mix requirements, rarely of choice on the part of those who are actually placing the concrete.

Effect of Excessive Sand.—Reference was made above to the undesirability of too large a proportion of fine aggregate in the mix. In considering this subject it must be kept in mind that some of the objections to too much fine aggregate are based on experience with fixed proportions, where an increase in fine material directly lowers the quality through the increase in the water required to produce the necessary consistency. When the subject is approached with the idea in mind of a fixed quality of the paste, it takes on an entirely new aspect, as can be seen from much of the discussion which has been brought out. Yet there are certain objections to grossly oversanded mixes, even when used with a paste of predetermined quality. Some of these may be very important in specific instances. Among the disadvantages of such mixes are the following: increased volume change, decreased weight and increased air voids.

Volume changes are discussed separately later. Reduced weight due to higher paste content of grossly oversanded mixes may be of considerable importance in gravity dams or other places where weight is required. Air voids are of principal significance in connection with the reduced weight. The lower weight in oversanded mixes is due to both

increased paste content and increased air voids. The proportions to use for any given set of materials to meet definite weight requirements can be determined by trial mixes with different proportions of fine and coarse aggregates mixed with the paste of required quality.

Effect on Volume Changes. The possible increase in volume change resulting from an excess of fine aggregate is probably the most important objection that can be raised to mixes of the oversanded type for ordinary construction requirements. In Tables V and VI, taken from tests by M. B. Lagaard and S. W. Benham at the Research Laboratory of the Portland Cement Association, are presented data on volume changes that will aid in fixing the limits of fine material in design of concrete mixes to meet specific requirements.

These data show the range in shrinkage which may be expected for various mixes and gradings for exposure in ordinary inside air for different periods of time. The specimens used in these tests were kept wet for 7 days before exposure to the air. The shrinkage shown, which is expressed in inches per 100 feet, represents the total change in length from the moist condition at 7 days to the age indicated.

TABLE V.—SHRINKAGE OF CONCRETE AND MORTAR

Specimen No.	Mix by volume	Water-cement ratio, corrected for absorption, gal. per sack	Paste-ratio by absolute volume, corrected for absorpton	Slump, in.	Shrinkage, in. per 100 feet.		
					7 days–28 days	7 days–3 months	7 days–6 months
258C	1:2:4	6.75	0.251	5	0.33	0.59	0.66
260C	1:2:2	7.00	0.339	$9\frac{1}{2}$	0.45	0.76	0.84
259C	$1:2\frac{1}{2}:3$	6.76	0.269	$6\frac{1}{4}$	0.30	0.57	0.62
261C	$1:2\frac{1}{2}:0$	7.17	0.451	$10\frac{1}{2}$	0.25	0.91	1.22
263C	1:2:2	5.49	0.306	$3\frac{1}{4}$	0.30	0.66	0.76
265C	1:1:2	5.60	0.377	$9\frac{1}{2}$	0.38	0.82	0.91
268C	1:1:1	4.74	0.448	$9\frac{1}{2}$	0.32	0.83	1.07
269C	1:1:0	4.88	0.616	11	0.34	1.06	1.49
270C	1:1:0	3.87	0.587	$3\frac{3}{4}$	0.36	0.88	1.24
272C	1:0:0	4.00	1.00	10	0.60	1.51	2.23

TABLE VI.—SHRINKAGE OF CONCRETE OF CONSTANT-WATER-CEMENT RATIO AND VARIABLE GRADING

Water-cement ratio = 6.6 gal. per sack, corrected for absorption. Nominal mix = 1:2:3½ by volume, unless otherwise noted. Shrinkage shown is for 358 days in ordinary air following 7 days of moist curing.

Specimen No.	Aggregate		Paste-ratio by absolute volume, corrected for absorption	Slump, in.	Shrinkage, in. per 100 feet
	Fine	Coarse			
278A	0–No. 4	⅜–¾ in.	0.275	7.50	0.620
280A	0–No. 4	No. 4–¾ in.	0.270	5.50	0.627
282A	0–No. 14	⅜–¾ in.	0.282	6.10	0.714
283A	0–No. 14	¾–1½ in.	0.282	6.25	0.689
284A	0–No. 14	No. 4–¾ in.	0.275	1.00	0.683
285A	0–No. 4	No. 4–1½ in.[c]	0.266	7.50	0.591
286A	0–No. 14	No. 4–1½ in.[c]	0.272	7.50	0.657
287A	0–No. 4	No. 4–1½ in.[d]	0.266	8.00	0.614
288A	0–No. 14	No. 4–1½ in.[d]	0.272	6.25	0.713
289A[a]	0–No. 4[b]	No. 4–1½ in.[c]	0.251	0.25	0.587
290A[a]	0–No. 4[b]	No. 4–1½ in.[d]	0.251	4.50	0.522

[a] Mix = 1:2.45:3.48.

[b] Intermediate size (between sieves No. 28 and No. 8) omitted.

[c] Graded (by weight): 25 per cent, No. 4–⅜ in.
50 per cent, ⅜–¾ in.
25 per cent, ¾–1½ in.

[d] Graded (by weight): 25 per cent, No. 4–⅜ in.
25 per cent, ⅜–¾ in.
50 per cent, ¾–1½ in.

The data in Tables V and VI do not lend themselves to an easy general interpretation. It will be seen, however, that the principal factor influencing shrinkage is the amount of the paste in a unit volume of concrete. This is shown in the fourth columns of the tables, the paste ratio being the volume of the paste in terms of the volume of the concrete. The water ratio of the paste is also seen to have some effect on the volume change. The influence of these two factors cannot be entirely separated, for any change in the water ratio results in a corresponding change in paste volume; this accounts for the fact that rich mixes do not show volume changes as greatly in excess of those for lean mixes as might be expected from the difference in cement content—the lower water ratios of the rich mixes

act to offset in quantity of paste the extra quantity of cement.

In considering the volume changes shown in Tables V and VI it should be remembered that the values for the later period are for almost complete drying out. The fact that the tests were on small specimens (mostly beams $4\frac{1}{2}$ by 5 by 19 in.) must also be kept in mind, as the size of the member affects the shrinkage through its effect on the rate and extent of drying. For ordinary building structures fully inclosed, values closely approaching those found by the tests may be reached, but for outdoor structures the shrinkage would be very much less for the several mixes. In very large structures exposed to both wet and dry periods the maximum shrinkage from the original length may never be even as great as the values shown for the 7- to 28-day period in Table V, owing to the fact that no opportunity is presented for extensive drying out of the large mass.

Practical Conclusions.- From the data presented it can be seen that, for special cases where volume changes must be kept at a minimum, the greatest importance attaches to the amount of paste in a unit volume of concrete. For such cases, therefore, the quantity of fine material should be kept as low as is consistent with proper workability. Sands containing large percentages of very fine material are especially to be avoided, as they require larger quantities of paste for the same water ratio and workability and therefore increase the shrinkage.

However, for the usual structure, where there is no special demand for minimum volume change, it can be seen from these data that a reasonable latitude is afforded in the proportions of fine to coarse aggregate without greatly affecting the volume change. For example, in Table V a comparsion of the 1:2:4 and 1:2:2 mixes of about the same water-cement ratio shows only about 25 per cent difference in shrinkage. This range in sand ratio is about as wide as need be required to realize the fullest possibilities of workability and economy. Intermediate

mixes in this range would give differences in volume change proportionately less. With even a 25 per cent difference in volume change, no difference in design is required except where the greatest refinement in the spacing of joints is attempted. Even for such refinement, if warranted, the only effect would be to require five contraction joints where four might have been used. Where some provision is made for volume changes on any reasonable basis, it is quite unlikely that 25 per cent variations from that basis would produce noticeable defects in ordinary construction. It is where no provisions at all are made that these volume changes give difficulty.

Summary of Grading Principles.—This discussion has shown that there is no fixed schedule of gradings or combinations of fine and coarse aggregate that can be set up as essential to good concrete construction or that is notably superior to many other combinations. The essential requirement is that, for a paste of given quality, the aggregate combination be such that the concrete can be placed properly and that it will not segregate either in placing or after it is in place. All the space between the aggregate particles must remain filled with the paste of desired quality.

It requires no elaborate theory of mixtures or cumbersome calculations to find aggregate combinations that will meet these requirements. The range within which they can be met without exceeding safe or sane limits in the cement quantity is wide enough to allow for considerable variations in materials and ample opportunities for economy. Any of the available materials that have been proved suitable as to cleanness, strength and durability can be utilized to their best advantage. Some restriction must be put (1) on the proportions of fine aggregate, to avoid mixes with high shrinkage factor, and (2) on the workability, to prevent an attempt to place mixes that are bound to result in honeycomb and stone pockets. The best method of finding the most suitable proportions is by trial. A number of mixes using paste of the required

water ratio can readily be made up in which the quantities of materials and the yield can be measured and notes made of the workability. From the results of these trials the mix best suited to the particular job can be selected. These trials can be by small batches or in full-sized batches in the mixer. In any case the water-cement ratios used should take into account the absorption, if dry aggregates are used, or the free water, if any, carried by the aggregate. This method is considered at length in Chapter VI.

CHAPTER VI

DESIGN OF CONCRETE MIXTURES

The two steps in the design of concrete mixtures to meet specific requirements have been stated in the first chapter and again at the opening of Chapter V.

These, however, will bear further repetition as they embody the essential message of this text.

Steps in the design of concrete mixtures:

1. Select the proportion of water and cement (the water-cement ratio) and the conditions of curing which will produce a paste to meet the requirements of strength and watertightness.

2. Find a combination of aggregates which, with the paste selected, will give a mixture that can be readily placed, but which will be of such plasticity that it will not segregate in handling or after it is in place.

The foundation for the first step has been thoroughly laid in Chapters I to V. In Chapter VII specific recommendations will be given for the selection of the conditions of curing and the water-cement ratio for different types of structures and degrees of exposure.

For the second step, the foundation has been laid in the discussions of Chapter V. It remains now only to develop more fully the idea of combining aggregates with the paste to obtain the necessary workability and plasticity by the simple expedient of trial batches.

One point to be kept in mind throughout this discussion is that no method of proportioning concrete should be made an excuse for neglecting the other details of construction. Selecting the proportions of ingredients to meet the requirements of the work is only one of the necessary steps in successful concrete construction. It goes without saying that the materials must be suitable; that the mixing,

transporting and placing must be such as to insure a homogeneous mass throughout the structure; and that adequate protection must be provided to obtain the curing necessary to develop the strength and watertightness required.

Method of Trial Mixtures

As brought out in Chapter V, the selection of aggregate combinations to meet the requirements of placing can best be done by trial. By this method several combinations of the available materials can be compared using a cement paste of the required water-cement ratio. The combination most suitable for the particular structure is judged by the relative workability of the mixes and their cost. The cost is determined by measuring the materials used and the yield of concrete for the several batches. The trials can be in small batches mixed by hand or full-sized batches in the mixer. Corrections, of course, are to be made in the water-cement ratio for free moisture carried by the aggregates.

By this same method, aggregates from several sources or of different gradings from the same source can be compared, the decision being based on the relative workability of the various batches and their total cost. In comparing the cost of mixtures differing in workability, consideration must be given to the relative cost of placing, for small advantages in cost of materials might easily be wiped out by an increase in the cost of handling and placing a less workable mix. In estimating such differences in cost of placing, allowance should also be made for possible delays which may result from the effort to use harsh-working mixtures.

Simplicity of the Method. This trial method of arriving at suitable proportions of aggregates is not nearly so formidable as many have assumed. Where only one fine and one coarse aggregate are under consideration, anyone familiar with concrete practice should arrive at approximately the right proportions in two or three trials. Even

one not thoroughly familiar with the handling of concrete should not require very many trials if he keeps in mind the two essential requirements—the specified water-cement ratio and a plastic mixture that can be properly placed. Let the first batch be anything that comes to mind. If this is very far from a reasonable mixture, it will be at once apparent even to a novice, and modification such as adding more paste or more aggregate can be made before the mixing is complete. Subsequent batches can be based on this first one, first increasing the proportion of fine and reducing the coarse, through a few stages, then varying in the opposite direction. It must not be forgotten that the studies in the other chapters of this text have shown that a considerable range in aggregate proportions does not materially affect either the quality or the cost of the concrete when a fixed water-cement ratio is maintained.

With a good working batch once obtained, further modification can be made as the work progresses, using the full-sized batches from the mixer as a basis of comparison. The different batches can be judged solely on the basis of how they place, or (by calibrating the skip or hopper) difference in yield can also be taken into account. Such a study of the concrete being placed is to be recommended even when the mix to use has been worked out rather carefully in advance, for it is finally the behavior on the work that measures the suitability of the mixture.

Using Aggregate of Maximum Weight.—Another method of arriving at the desired proportions from trial batches is to begin with the combination of fine and coarse aggregate which gives maximum weight of mixed aggregate. The proportions required to give maximum weight can be determined by trial. For aggregates of approximately the same specific gravity, that combination which gives maximum unit weight dry will also give approximately the greatest yield of concrete for a given quantity of cement and its fixed proportion of water. By making the first trial batch from this combination of aggregates, a few trials, first in one direction and then in the other, should quickly result in the most desir-

able combination considering workability, cost, etc. The discussion of the limitations on the proportion of fine aggregate in Chapter V should be reviewed in this connection.

Where fine and coarse aggregates are available from several sources, the number of trial batches can be reduced by a preliminary study of the aggregates alone to find the proportions which give the greatest unit weight of mixed concrete for each fine aggregate combined with each coarse. Trial batches of concrete can then be limited to the combinations of mixed aggregates of maximum weight. These trials should give information through which all but one or two combinations can be eliminated from further consideration. The most favorable combinations can then be studied in more detail, using proportions of fine to coarse varying in both directions from those giving maximum weight. From these more detailed studies the most economical mixtures giving the necessary workability with the given water-cement ratios can be determined in the same manner as when only one sample of fine and one sample of coarse are available.

Interrelation of Mix, Water-cement Ratio, Cement Factor and Consistency

Supplementing the discussion of Chapter V, the following study of the various factors affecting the workability and economy of concrete mixtures will be found helpful.

The interrelation of the four factors—mix, water-cement ratio, cement factor and consistency—is well brought out by the diagrams of Figs. 21 and 22. These are reproduced from a paper by W. R. Johnson and the writer in the report of the Director of Research of the Portland Cement Association, November, 1928. They show the results of a very extensive series of tests of concrete made from two different aggregate combinations (Elgin sand and gravel, and Elgin sand and Chicago limestone) in which the mixes and water-cement ratios were varied over a considerable range. The sand was graded from 0 to the No. 4 sieve, and the coarse aggregate between

the No. 4 sieve and $1\frac{1}{2}$ in. In these diagrams the water-cement ratios have been corrected for absorption of aggregates.

Before pointing out some of the features of these diagrams attention is called to the fact that the curves are not for general application, as they are based on these two materials only. Materials of other size, grading or surface characteristics would not show the same quantities of cement or the same slump for the given mixes and water ratios. The curves are useful, however, in establishing certain general relationships which would be similiar with other materials.

Sets of curves similar to those of Figs. 21 and 22 drawn for several different types of materials would serve as a very good guide for general use in designing mixtures for materials of these types.

It will be noted that Fig. 21 shows four sets of curves, two for each kind of aggregate for the two water-cement ratios of 5 and 6 gal. per sack. The groups are arranged for easy study and comparsion. Figure 22 shows similar curves for water-cement ratios of 7 and 8 gal. per sack. The mixes shown are expressed in the common manner: 1 cement, x sand, and y coarse aggregate, except that the volumes are on the basis of dry, compact materials. For each family of mixes and each water-cement ratio in these diagrams a single curve shows the change in cement quantity (sacks per cubic yard of concrete) and consistency (slump), as the amount of coarse aggregate is changed within the given mortar family.

One feature of the diagrams of Figs. 21 and 22 that should be emphasized is the relative position of the curves for the different families for each water-cement ratio. It will be noted that the curve for one family of mixes occupies a position on the diagram lower than that for any other family, but that no one family is the lowest in the several groups representing the different water-cement ratios. In general, either the curve occupying the lowest position, or the one immediately above it, contains (within the range of slumps from about 2 to 6 in.) the mixes for that

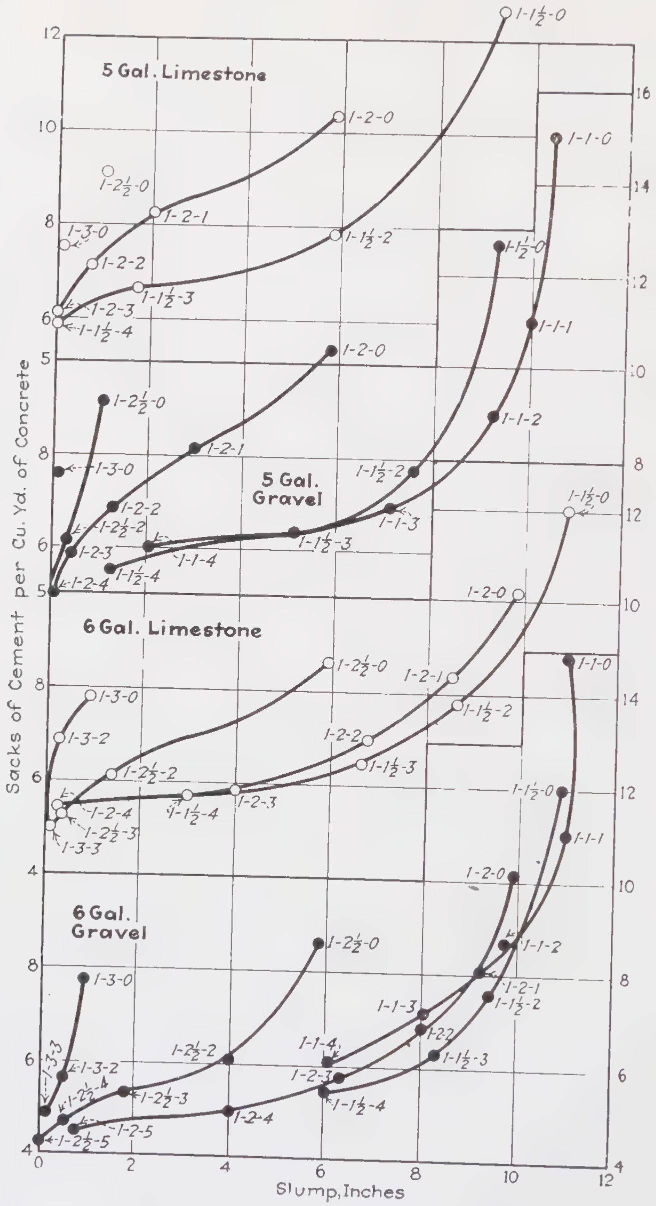

FIG. 21.—Interrelation of mix, water ratio, cement factor and slump. These curves are for these materials only. Other materials will not give the same cement factor and slump for corresponding mixes and water-cement ratios.

family in which the ratio of fine to coarse aggregate is not greater than 1:1 or less 1:2. Within this range of slumps also the grossly oversanded mixes are high in cement factor. Thus the mixes which are the more desirable in the light of the other considerations which have been discussed—shrinkage, weight, etc.—are seen to be among those comparatively low in cement factor. This bears out the point made in the discussion that when working with a fixed water-cement ratio the natural tendency to avoid non-workable mixes on the one hand, and mixes high in cement factor on the other, would lead to the use of mixes most desirable from other considerations.

Fixed Cement-sand Ratio.—In the light of what has just been brought out it is of interest to consider the suggestion that has sometimes been made of applying water-ratio control by the use of a 1:2 mortar with a fixed water ratio, allowing workability to be adjusted by merely changing the coarse aggregate quantity. It can be seen from Figs. 21 and 22 that such a method, while entirely practicable, would certainly result in loss of economy for some water-cement ratios and materials. For example, in the 5-gal. mixes of Fig. 21, the 1:2 mortar is certainly not the most desirable. Likewise, for the other water-cement ratios, intermediate families like the 1:1$\frac{3}{4}$ or the 1:2$\frac{1}{4}$ might easily show an advantage. Differences in sands would also have an influence on the economical cement-sand ratios. The better method is to leave the aggregate proportions as wide open as possible, fixing only those limits which are necessary to insure proper workability and to avoid extremes in unit weight or cement factor.

Overwet Mixes Uneconomical.—Figures 21 and 22 show very clearly the great disadvantage of the overwet mixes. With the water-cement ratios fixed, it is seen that for slumps much above 6 in. the cement factor increases very rapidly for additional slump. This is one of the factors that can be depended upon to prevent extremely wet mixes where the water-cement ratio is to be fixed.

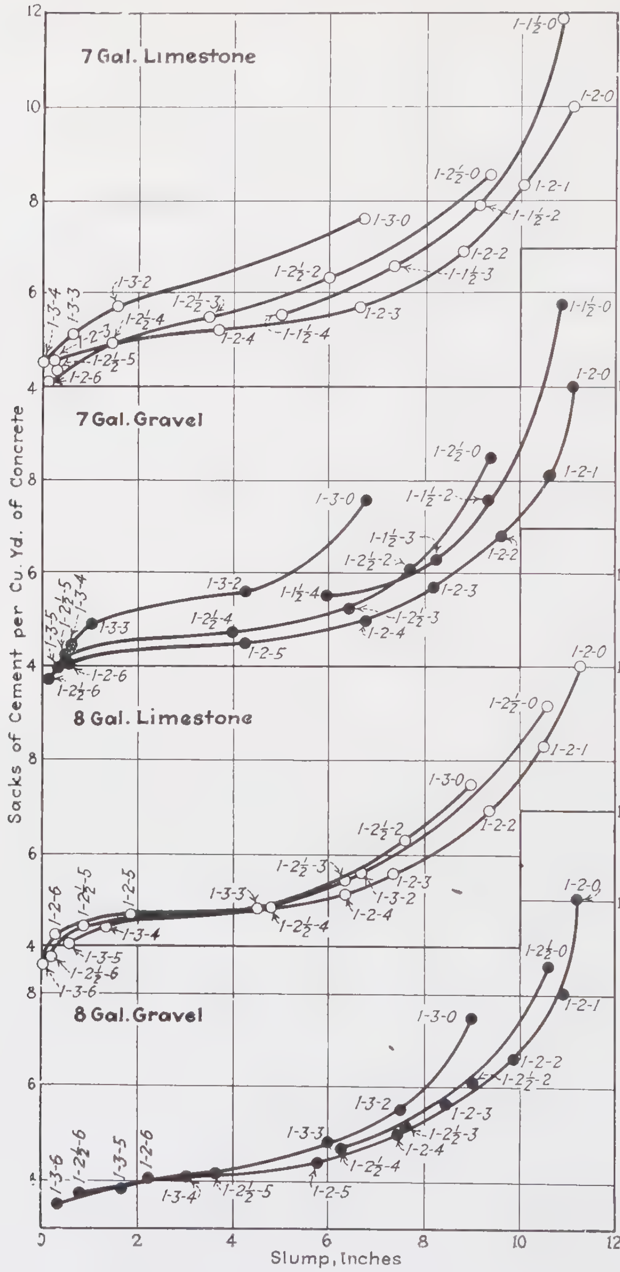

FIG. 22.—Interrelation of mix, water ratio, cement factor and slump.

These curves are for these materials only. Other materials will not give the same cement factor and slump for corresponding mixes and water-cement ratios.

Constructors who formerly felt the need of a very wet concrete will respond rather quickly to the suggestion for less fluid mixes when it is seen that a change from a 9- to a 6-in. slump, for example, means the saving of more than one sack of cement per cubic yard.

These curves also show that the saving in cement by the use of very dry or harsh mixes is very small and will not at all compensate for the extra cost of placing. It is interesting to note that for most of the diagrams the range in slump of from 2 to 6 in. embraces portions of the curves that are nearly horizontal. This shows that within this range the best control of consistency can be exercised with little or no change in cement factor.

Further Improvement in Concrete Practice

The discussions of Fig. 1 in Chapter II and of Fig. 20 of Chapter V have shown certain limitations in the present methods of making concrete and point the way to any major improvements which may be made in concrete practice. In the discussions of these figures it was brought out that, regardless of the aggregate combinations or quantity of cement, a certain amount of water per unit volume of concrete will remain in the mass in a more or less uncombined state. This extra water is required to give mobility to the mass in order to make it possible to place the concrete and give a homogeneous structure. Grading can do but little to improve this condition, as shown by a study of Figs. 1 and 20 and the discussion of the preceding Chapters. At best, only a bare 5 per cent of the concrete volume in plastic mixtures can be changed from water into solid material by improvements in grading over what is ordinarily accomplished. This leaves from 8 to 12 per cent of water, as shown in the figures. It is toward the reduction of this quantity of water that any proposed improvements must be directed.

By using richer mixes the proportion of the uncombined water in the paste is reduced to the point where the paste becomes watertight to almost any desired degree, even

though the total water per unit volume of concrete is not materially lowered. But extremely rich mixes are undesirable, so the opportunities for major improvement must be sought elsewhere than in matters of grading or richness of the mix.

Better Curing. Improved curing to force more and more of the water into the permanent solids of the mass has been emphasized. This is important, and the test data quoted, as well as experience, have shown that it offers the greatest single opportunity for better concrete under our present methods.

Obviously there is a limit to the amount of water that can be combined with a given quantity of cement, so that complete exclusion of uncombined water from the concrete is not possible by extended curing. In this connection it may not be amiss to suggest to those who are looking for a panacea in the form of some new cement that these same limitations will still exist if the concrete is to be placed in a plastic condition. Either extra quantities of the cement must be used to combine with all the water or uncombined water will exist in the mass.

Methods of Placing and Treatment.—These comments suggest the other lines along which improvement can be made. These are two—namely, first, *the removal of excess water after the concrete is in place*, at the same time consolidating the mass; and second, the placing of concrete by some method *that will insure* without the use of extra water *the same degree of consolidation, the same complete filling of the mass with the cement paste*, that is obtained with the plastic mixtures. There are good examples where both of these methods have been used successfully, but neither has been developed for general application to the degree that its merit warrants.

It is not the purpose here to elaborate on the possibilities of these methods of placing concrete, but only to point out that results in full accord with the fundamental principles of this series of discussions can be expected from them. It can be readily seen that any method of

placing which extracts water from the mix as it is being deposited, in such manner that the space occupied by this water is at once filled by the consolidated concrete, accomplishes the desired end. In such a method the advantage of plastic mixes in mixing and handling is retained, while the disadvantage of the large proportion of uncombined water is eliminated.

The use of an absorptive sand mold in the making of cast stone is a common illustration of this method. Probably the most notable illustration is the work of John J. Early in placing concrete in the "Fountain of Time" at Chicago ("Building the 'Fountain of Time,'" by John J. Early, *Proc.*, Am. Concrete Inst., Vol. 19, p. 185, 1923). The Bruner patented method of placing floor finish is still another illustration.

Placing concrete with less water than is required for plastic mixtures was long practiced, and many examples of early structures in excellent condition today bear evidence of the possibilities of the method. In these structures fairly lean mixtures were placed in thin layers in semi-dry condition and thoroughly rammed until water flushed to the surface. This flushing of the water to the surface as a result of the ramming was evidence that the space between the aggregate particles was thoroughly filled with the paste. The paste was of high quality because of its low water-cement ratio, which accounts for the excellent condition of many of these old structures. The patchy appearance of some of the structures shows the difficulty of always getting proper ramming and thorough bonding of successive layers.

The purpose of these comments is not to advocate the return to this method of placing, but to suggest that mixes too stiff for plastic consistency might be placed successfully by some mechanical means. The requirements for such a method are easily visualized from this discussion. The net result of the operation must be a mass in which the spaces between the aggregate particles are everywhere filled with the paste of desired water-cement ratio. Thus,

by starting out with a mixture in which the quantity of paste is insufficient to give a plastic mass, the space between the aggregate particles is so reduced by mechanical means that finally it is completely filled by the paste.

In all of these methods the proportioning of the aggregates can readily be done by trial mixtures using a paste of the desired water ratio, just as in the case of mixtures to be placed in a plastic condition. Under these suggested methods of placing, if the aggregates are finally completely incorporated in the paste, the properties of the concrete will be principally measured by the properties of the paste just as in the case of plastic mixtures.

CHAPTER VII

SELECTION OF CURING PERIOD AND WATER-CEMENT RATIO

In the preceding discussions the basic principles of concrete mixtures were established. In those to follow it will be the purpose to present some of the considerations which are necessary for applying these principles to a particular structure. In this chapter, attention will be given to the establishment of maximum water-cement ratios and minimum curing requirements. In the succeeding chapters attention will be given to such matters as the selection of the aggregates, measurement of materials, mixing, transporting, and placing the concrete.

Minimum Curing Period

It was brought out in the discussion of Figs. 8 and 9 in Chapter III that water-cement ratio and degree of chemical combination are interrelated in the development of strength in the cement paste. Changing either factor—the water-cement ratio or the degree of curing—does not alter the importance of the other factor. Thus, within certain limits, a particular strength or watertightness can be developed by several different water ratios, provided the concrete in each case receives the appropriate degree of curing.

Effect of Temperature.—This relation between temperature of curing, water-cement ratio and strength is nicely brought out by the curves in Fig. 23, which show the effect of both the water-cement ratio and the temperature on the compressive strength of moist-cured concrete at different ages. The curve for the 28-day strength at 70 deg. F., is that first given by Abrams and corroborated by many subsequent tests. The curves for

70 deg. F. at the ages of 1, 3 and 7 days are based on tests in the Research Laboratory of the Portland Cement Association, using the regular laboratory mixture of equal parts of four standard portland cements. The curves for the other temperatures for all ages were deduced from the curves for 70 deg. F. on the basis of data given in Bull. 81 of the Engineering Experiment Station of the University of Illinois, "Influence of Temperature on the Strength of Concrete," by A. B. McDaniel.

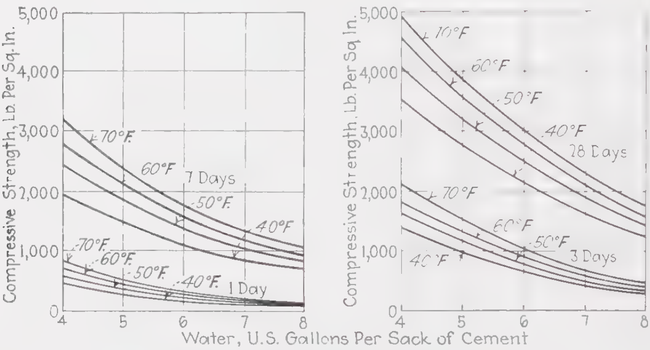

FIG. 23.—Water-cement ratio strength relation for moist curing at different temperatures.

An illustration from the curves of Fig. 23 will show the necessity of fixing some degree of curing before selecting a water-cement ratio for definite strength requirement. From these curves, for example, it can be seen that a strength of 2000 lb. per square inch can be obtained by any of the following combinations:

Water-cement ratio, gal. per sack	Temperature, deg. F.	Age, days
4	70	3
5	60	7
$5\frac{1}{2}$	70	7
6	40	28
$7\frac{1}{2}$	70	28

The other data which have been presented indicate an equally important effect of the curing on the water-cement ratio required for a particular degree of exposure.

Variable Job Conditions.—The usual practice in regard to the strength of concrete has been to specify mixtures or water-cement ratios on the basis of the strength shown for 28 days moist curing at 70 deg. F. This has been accompanied by some more or less nominal requirement in the the specification as to protection to be given on the work, the assumption being that, with some protection during the first few days, the concrete in the structure will eventually exceed the strength corresponding to the 28 days moist curing. Experience has shown that this is generally true, due to two primary factors. First, completely adverse weather conditions are quite rare, and even though the protection is removed some normal increase is to be expected which does not cease at the 28-day period. Second, the practice of testing the moist-cured laboratory specimens in a saturated condition, upon which the greater part of our knowledge is based, gives a strength value only about 80 per cent of that shown when the specimen is reduced to an air-dry condition comparable with that in the concrete of the structure when put into service.

In large mass construction the conditions may be quite favorable, due to the slow evaporation from a large volume of concrete. This slower evaporation is especially favorable in localities where rainy spells occur only a few weeks apart. Large volume is also an advantage in cold weather, as the heat generated by the reactions of setting and hardening is considerable in large masses. These are fortunate circumstances, because structures of this type are usually those which have to resist the weathering effects of the elements. In the case of buildings or other structures of thin sections, the conditions are quite the reverse. In summer, the free circulation of air on all sides of the thin members causes rapid evaporation, whereas in the winter there is no mass effect to conserve

either the heat generated by the chemical reactions or that applied to the materials for protection during the early period. If the concrete in buildings were generally required to be watertight, the usual curing methods employed would probably be found inadequate, in spite of the fact that in most cases the mixes are potentially capable of producing watertight concrete. In road slabs the conditions for curing are extremely unfavorable owning to the large unprotected area exposed to the direct action of sun and wind. This, combined with the severe service which the roadway must meet, has made curing one of the principal problems of road construction. Highway engineers have long recognized this difficulty and have done much in the development of curing methods.

Recommended Curing Periods.—Obviously, exactly the same conditions cannot be expected in all cases, but in view of the importance of curing, particularly in the early period, it would seem both sound and reasonable practice to require a certain minimum period of controlled conditions. Any unfavorable conditions following this cannot reduce the quality of concrete below that intended, and any specially favorable condition can merely add to the factor of safety.

In Table VII, where recommended water-cement ratios are given to meet different conditions of exposure, a minimum curing condition has been assumed that will be the equivalent of that obtained when the concrete is protected from the loss of moisture for at least 10 days at a temperature of 70 deg. F. Where the conditions following this period are to be unfavorable (thin sections in hot, dry air or in low temperatures), the only way to meet this requirement is definitely to require the full 10 days of moist curing at 70 deg. F. Where the subsequent conditions are to be favorable to continued hardening (mass concrete in moist air at moderate temperatures), this period can be somewhat shortened. However, no concrete structure should be exposed to drying conditions before 5 days of moist curing at a temperature of

60 deg. F. or more, unless the water-cement ratios have been selected with this in view.

The above-mentioned minimum requirements contemplate some continued chemical action for considerable periods beyond the 10 days. Without this favorable beginning, however, such continued activity cannot be assured. These limits are recommended as suitable for most specifications, with the suggestion that for special conditions additional curing may be the most desirable way to obtain the required results.

Selection of the Water-cement Ratio for Strength

From the foregoing discussion it can be seen that the water-cement ratio to use for definite strength requirements cannot be selected without first taking into consideration the curing conditions that are to prevail. Following the line of reasoning in that discussion, it is recommended that, for the ordinary structural requirements, the usual practice be followed of selecting the water-cement ratio on the basis of strength tests at 28 days in which specimens are moist cured at 70 deg. F. and tested wet. When this is done, the curing of the structure should be the equivalent of that recommended above as the minimum curing period.

Job Curves.—Whenever possible, strength tests should be made for each particular project using the identical materials—cement, aggregates and water—intended for the structure. This may be of considerable importance where unusual materials are encountered. When this is done, the procedure should be that outlined below giving a "job curve" as a basis for design. In the absence of such tests, the curve in Fig. 23 can be taken as satisfactory for *average materials where good workmanship and careful measurement of the water will be assured.* This curve is that first given by Abrams and has been found to be a satisfactory basis for design under these conditions.

As pointed out in Chapter III, the greatest difference between various cements lies in the strength at the early

ages. For that reason the curves in Fig. 23 for the 1-, 3- and 7-day periods cannot be used with so great reliability as those for the 28-day periods. Where the strength at early ages is to be a governing feature of the work, the use of special tests to obtain a "job curve" as mentioned above will be particularly advantageous. These curves in Fig. 23 for the early ages, however, can be taken as indicative of the average results which may be expected from a wide variety of cements. The curves may be very useful, also, in showing the relation between the strength and the temperature of curing.

Where tests are to be made to determine the water-cement ratio strength relation for the particular materials to be used, they should generally be on the basis of moist curing at 70 deg. F.; the specimens being placed in the moist room (or under water or wet sand at 70 deg. F.) 24 hours after casting and kept there until tested. By following this procedure the results will be directly comparable with any subsequent tests which may be made on the work and with the vast literature of concrete, which is principally recorded in terms of the 28-day tests on this basis.

Follow-up Tests Desirable.—As a check on the effectiveness of the protection being afforded the structure, tests should be made from time to time on specimens to which protection has been given comparable with that given the structure itself. Identical protection for the specimens and the structure is difficult to obtain owing to the greater loss of water and change of temperature in the small isolated specimen, as compared with the larger structural members. However, if care is taken to get proper protection, the test results will give a reliable indication of the quality of the concrete in the structure. Such tests can be very useful in fixing the periods when forms may be removed or the structures opened to service. If the curing conditions have been unfavorable, these "follow-up tests" will give a basis for fixing such additional curing as may be necessary.

In special cases it may be desirable to base the job curve for the design of the mixes on tests of specimens

cured under conditions as nearly identical as possible with those to be encountered on the work as in the case of the "follow-up" tests. This is more apt to be desirable where a definite strength at some early period is attempted, either through the use of rich mixtures of normal concrete or by special rapid-hardening cements. Under such conditions the field-cured specimens may be preferable. Ordinarily, however, the standard curing is to be preferred, as it gives the potential quality of the concrete. Where only the field-cured specimens are used, deficiencies in strength due to mixtures or materials might be ascribed to improper curing or vice versa.

In making tests for the establishment of a job curve showing the water-cement ratio strength relation, there should be included a sufficient number of water-cement ratios to give several points on the curve with a number of specimens for each water-cement ratio. Standard procedure should be followed in making the tests and the mixes and consistencies used should be approximately those which are likely to be used on the work.

Selection of the Water-cement Ratio for Durability

The major influence of the water-cement ratio on the watertightness of the concrete and therefore on its durability has been brought out. Unfortunately, the data available do not lend themselves to the establishment of a direct relation between the water-cement ratio and some required degree of durability as is possible in the case of strength. Any decision therefore as to the water-cement ratio to use must be based on a study of the performance of structures in service in connection with the available data on freezing and thawing, and permeability. Almost every effort to analyze the performance of structures meets with some difficulty because of the meager character of the records relating to the mixes, water-cement ratios, materials and other factors at the time of construction which have contributed to the present condition of the structures.

TABLE VII.—RECOMMENDED WATER-CEMENT RATIOS FOR CONCRETE TO MEET DIFFERENT DEGREES OF EXPOSURE

These requirements are predicated on the use of concrete mixtures in which the cement meets the present standard specifications of the A. S. T. M. and to which an early curing is given that will be equivalent to that obtained when protected from the loss of moisture for at least 10 days at a temperature of 70 deg. F. Also that the concrete is of such consistency and is so placed that the space between the aggregate particles is completely filled with cement paste of the given water ratio.

	Water-cement ratio, U. S. gal. per sack[1]		
Exposure / Class of structure	Reinforced piles, thin walls, light structural members.	Reinforced reservoirs, water tanks, pressure pipes, sewers, canal linings, dams of thin sections.	Heavy walls, piers, foundations, dams of heavy sections.
Extreme: 1. In severe climates like in northern U. S., exposure to alternate wetting and drying, freezing and thawing, as at the water line in hydraulic structures. 2. Exposure to sea and strong sulphate waters in both severe and moderate climates.	$5\frac{1}{2}$	$5\frac{1}{2}$	6
Severe: 3. In severe climates like in northern U. S., exposure to rain and snow, and freezing and thawing, but not continuously in contact with water. 4. In moderate climates like southern U. S., exposure to alternate wetting and drying, as at water line in hydraulic structures.	6	6	$6\frac{3}{4}$
Moderate: 5. In climates like southern U. S., exposure to ordinary weather, but not continuously in contact with water. 6. Concrete completely submerged, but protected from freezing.	$6\frac{3}{4}$	6	$7\frac{1}{2}$
Protected: 7. Ordinary inclosed structural members; concrete below the ground not subject to action of corrosive groundwaters or freezing and thawing.	$7\frac{1}{2}$	6	$8\frac{1}{4}$

[1] Free water or moisture carried by the aggregate must be included as part of the mixing water.

Recommended Water-cement Ratios.—Recognizing these difficulties, the author has nevertheless attempted from such information as is available to set up a guide for the selection of the water-cement ratio to use for different classes of structures and degrees of exposure. These recommendations are given in Table VII. They are intended to apply only when plastic and homogeneous mixtures are used and when the cement meets the present standard specifications of the American Society for Testing Materials. They further assume a minimum curing, equivalent to that obtained when protected from the loss of moisture for at least 10 days at a temperature of 70 deg. F. Naturally, if the strength requirement for a particular structure exceeds that to be expected from these water-cement ratios, the more severe requirement should govern.

In presenting these recommendations, the limitations of the basic data are fully recognized. It is appreciated that examples can be cited where satisfactory results have been obtained with water-cement ratios greater than those indicated; also that unsatisfactory experience has resulted from the use of perhaps even lower proportions of water. It is believed, however, that for the conditions indicated, the recommended water-cement ratios are safe and yet not unduly conservative. As pointed out elsewhere, where the curing conditions are less favorable than indicated in the table or where the curing period must be shortened, the water-cement ratios should be reduced.

Correction of Water-cement Ratio for Free Water and Absorption

It has been pointed out in the earlier Chapters that the quantity of water in the paste which is effective in determining its properties is that actually in the paste as the concrete lies in place at final consolidation. Any water that is lost from the mixture during transportation and placing is properly deductible from the quantity of water added at the mixer in computing the true water-cement ratio. Such loss of water may be through evap-

oration or through absorption by the aggregate. In hot, dry weather with dry aggregates these losses may be very considerable and justify making additions of water at the mixer to allow for them.

In the same way free water or moisture in the aggregates must be taken into account in computing the water-cement ratio. Most sands and gravels are now the product of wet screening plants and come to the job with varying amounts of free moisture. For proper control of the concrete it is necessary that the amount of this free water be known so that the water added through the measuring device can be adjusted to give the required water-cement ratio. There are a number of methods of measuring the water carried by aggregates which can be used successfully on the job without expensive or elaborate equipment. These have been described in technical papers and committee reports in recent years. The reader is referred to the *Proceedings* of the American Concrete Institute and of the American Society for Testing Materials for these descriptions.

The method of drying over an open fire or oil stove is still quite widely used and is perfectly satisfactory. A variation of this method consists in spraying the aggregate sample with alcohol and igniting. Two or three applications of small quantities of alcohol will serve to dry thoroughly a very wet sample. When drying the sample to establish the quantity of free moisture in the aggregate, it is necessary to know what portion of the water driven off is free water which would become part of the mixing water in the concrete, and what portion is in the aggregate in the form of absorbed water which would remain in that form and have no effect on the water-cement ratio. This is best determined by driving off all the water and subtracting the amount which the aggregate can absorb, the latter being determined by a separate test for absorption.

CHAPTER VIII

SELECTION OF AGGREGATES

Grading

In Chapter VI, the selection of aggregates with respect to grading was considered. It was there pointed out that the most desirable grading to use could be determined from a series of trial mixtures in which the available materials are compared as to workability and economy. The limitations that should govern in the proportions of fine and coarse aggregate were given in Chapter V. These two chapters should be reviewed when selecting aggregates for a particular job.

Strength and Durability

In all the foregoing discussion it has been assumed that the aggregates are suitable as to mineral composition and physical characteristics. Fortunately, most of the common aggregate materials are suitable in these respects, but occasions frequently arise when some determination must be made as to these properties. In the following paragraphs, recommendations are made regarding the ordinary impurities which occur in natural aggregates. Methods are also suggested for determining the suitability of aggregates in respect to strength and soundness.

Impurities.—In the matter of cleanness and freedom from impurities, it is difficult to set up rigid limits which separate desirable from undesirable aggregates. The following limitations have been abstracted from the tentative specifications adopted by the American Concrete Institute in February, 1929. These may be taken as satisfactory for the ordinary deleterious substances. The exact percentage which might in certain cases be permitted could

vary somewhat from those given. The 1 per cent limit on shale seems unduly restrictive. For ordinary conditions, from 3 to 5 per cent, would not be objectionable. Except for the undue restriction on shale content, the maximum of 5 per cent of the total impurities, which is intended to apply to the fine and coarse aggregates separately, seems to be a reasonable requirement.

Deleterious Substances.

2. (*a*) The maximum percentages of deleterious substances shall not exceed the following values:

	Per cent by weight	
	Fine aggregate	Coarse aggregate
Removed by decantation	3	1
Shale	1	1
Coal	1	1
Clay lumps	1	$\frac{1}{4}$
Soft fragments	..	5
Other local deleterious substances (such as alkali, mica, coated grains, soft and flaky particles, friable, thin, elongated or laminated pieces)		

NOTE.—It is recognized that under certain conditions maximum percentages of deleterious substances less than those shown in the table should be specified.

(*b*) The sum of the percentages of shale, coal, clay lumps, soft fragments and other deleterious substances shall not exceed 5 per cent by weight for either the fine or coarse aggregate.

(*c*) All fine aggregate shall be free from injurious amounts of organic impurities. Aggregates subjected to the colorimetric test for organic impurities and producing a color darker than the standard shall be rejected unless they pass the mortar strength test as specified in section 4.

The requirement for a colorimetric test is now quite general and seems to be warranted by experience in the field under average conditions. There are localities, however, in which aggregates carry certain impurities that give a dark color in the test but which do not reduce the strength of concrete in which they are used. Lignite is an example of such an impurity; nevertheless it should

not be permitted in considerable quantities where surface appearance is important. Aggregates which make an unsatisfactory showing in the colorimetric test should not be used unless their suitability is established by strength tests.

Strength of Aggregate. The suitability of the aggregate as regards strength can, of course be determined by tests in concrete mixtures in comparison with the aggregates of known quality, using the water-cement ratios specified for the particular structure. In such tests it may be desirable to include also water-cement ratios somewhat lower than are intended in the structure. The increased strength from these richer mixes will be influenced in some degree by the protection offered by the paste, but they should disclose any serious weakness of the aggregate that might not become evident in short-time tests with the water-cement ratios specified.

Soundness of Aggregate.—The durability of an aggregate cannot be determined so easily as its strength. In most localities there are sources of aggregates which have been long in use and which have given satisfactory service. When aggregates are available from such sources, no special study or tests need be made. When, however, new sources of supply are to be opened, it is desirable that some examinations and tests be made before accepting the material for use. This is particularly important in structures that are intended for extreme or severe exposure, for even though a good quality of paste may offer considerable protection to the aggregate particles, any weakness of the aggregates themselves may eventually develop in such exposure and disrupt the concrete.

Where the aggregate is to be crushed from the ledge rock, a thorough examination of the ledge itself gives the best indication of the ability of the rock to withstand weathering. Such an examination, of course, should cover all the strata which are to be included in the quarrying operations at points where they have been exposed for long periods of time. Failure to observe these pre-

cautions may result in disappointment, for many rocks which appear sound and durable in a freshly opened quarry face will disintegrate upon exposure to the destructive forces of weathering.

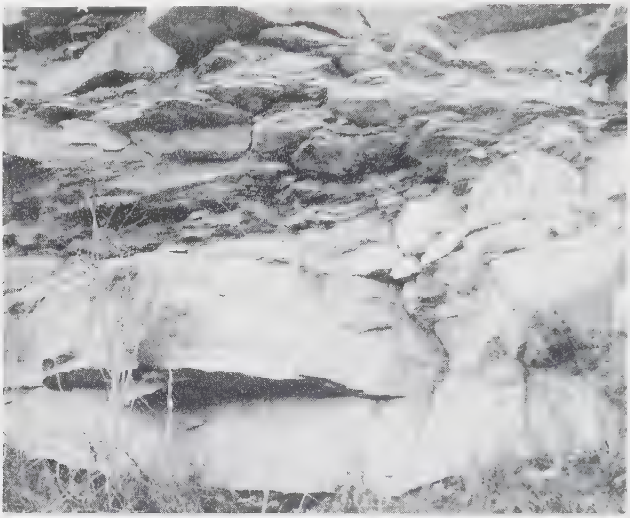

FIG. 24.—Portion of a quarry face after 16 years exposure showing disintegrated strata of limestone.

Test for Soundness.—A test that is now quite commonly applied to determine the soundness of aggregates consists in the immersion of the rock in a sodium sulphate solution alternated with periods of drying in an oven. The samples are kept immersed for twenty four hours in a saturated solution at 70 deg. F., after which they are dried for 4 hours at 212 deg. Samples which exhibit marked disintegration after five repetitions of this treatment are considered to be unsound. While this test has not been thoroughly coordinated with the performance of aggregates in structures, it is quite generally considered as providing a useful measure of durability. It is probable that a larger number of cycles than five will be necessary if this test is to be the sole reliance in estimating the durability of aggregates.

Examples of Unsound Aggregates in Concrete.—Figure 24 shows a picture of a limestone deposit in which some

of the strata are definitely unsound. Figure 25 shows a portion of a concrete structure which was built using aggregates from this deposit. The portion shown in Fig.

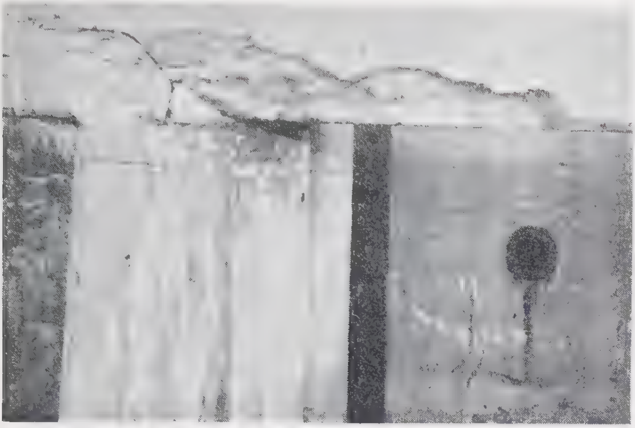

FIG. 25.—Portion of a concrete structure in which coarse aggregate from the quarry shown in Fig. 24 was used.

24 was the working face of the quarry during the period when the structure was being built. The disintegration of some of the strata, which is clearly shown in the illustration, has all taken place during the 16 years that this

FIG. 26.—Specimen of concrete in which unsound coarse aggregate has contributed to the disintegration.

quarry has remained idle. The appearance of the concrete in Fig. 25 is characteristic of that resulting from the use of unsound aggregates.

Another example of concrete in which unsound aggregate has largely contributed to the disintegration is shown in Fig. 26. The coarse aggregate used in this structure is a weathered limestone slightly seamed with calcite which failed to pass the sodium sulphate test. The characteristic effect of unsoundness, shown in this illustration, will develop rapidly or slowly, depending on the properties of the cement paste. Where the exposure is not too severe and the cement paste is very impervious, the unsoundness may never be disclosed. However, with an aggregate of doubtful quality, too much reliance should not be placed on the protection offered by the paste unless the record of performance includes its use where the exposure has been sufficient to provide a thorough test of its weathering qualities.

CHAPTER IX

IMPORTANCE OF PROPER CONSTRUCTION METHODS

It does not come within the scope of this book to cover in detail all the operations incident to good concrete construction. It is, however, within its scope to set up the basic principles which should guide in the choice of construction methods and in their execution in order to assure that the concrete will be uniform throughout and of the desired quality. Such a limited treatment is all that is attempted in this, the concluding chapter.

Measuring Materials

The principal requirement in measuring the aggregates is that of uniformity. Not only is it important that the quality of the concrete be the same from batch to batch, but uniform consistency is equally necessary, for haphazard changes in consistency make it difficult to avoid segregation in placing. Such changes also add materially to the placing cost, since nothing so disorganizes the placing of concrete as to have the batches fluctuate from fluid to stiff, particularly where placing is difficult.

The selection of equipment for measuring aggregates will depend upon many factors, and no general recommendation can be made regarding it. The two most important considerations are the extent to which uniformity in the concrete is to be maintained, and the character of the aggregates. The source of aggregate supply must receive consideration and purchase specifications should be drawn to secure the constant delivery of the kind of materials for which the plant is designed. If the aggregates vary considerably, either in grading or in moisture content, weighing equipment will prove very desirable where great uniformity is demanded. Where the aggre-

gates come to the work with little change, either in grading or moisture content, batcher plants giving volumetric measurement can satisfy the most exacting requirement. Some of the special devices now in the market for measuring aggregates in combination with water offer certain advantages under many conditions.

In any case means for accurate measurement of the water should be provided, as this is essential for uniformity in the quality of the paste and in the consistency of the concrete. The method of measuring water should be such as will permit of the necessary adjustment to compensate for variations in moisture carried by the aggregates.

As the practice of designing mixes for definite quality comes into more general use the demand for more accurate measurement of materials will grow, for it requires only a casual contact with a job where real quality control is attempted to realize that ultimate perfection can be achieved only through mechanical means. The progress that has been made in the past few years sustains this prediction.

Mixing

About the only requirement of the mixing operation which is definitely recognized is that of uniformity, and even in this respect there is no exact measure of performance. Any beneficial action in the mixer other than providing a uniform distribution of materials has not been definitely established. Practically all the information available in regard to mixer performance is limited to the results of strength tests of concrete and is confined principally to the effect of variations in speed of the drum and duration of mixing. All the available tests show a rapid increase in strength with time of mixing up to a certain point, followed by a much less rapid increase for longer periods. This point of change is not the same for the various groups of tests, but has usually come within the limit of from $\frac{3}{4}$ to 2 minutes. An important factor is the

consistency. Mixes which are stiff from high cement content and dry mixes require longer mixing time than the more fluid ones.

FIG. 27.—Buttress of a dam after 20 years exposure, showing the disintegration due to accumulation of water and laitance.
Note the disintegration at the top of a layer and the sound concrete at the bottom.

In view of the lack of information on the factors contributing to this increase in strength with time, it would seem a logical procedure to maintain some time limit in specifications, at least until such time as a more definite

criterion of the desired performance in the mixer is found. Such data as are available indicate that for the usual concreting operations with plastic mixtures, the limit should not be less than one minute after all the ingredients

FIG. 28.—Another example of disintegration at points where excess water has accumulated in placing.

are in the mixer. For very stiff or dry mixes it should be $1\frac{1}{2}$ minutes or longer. In other cases also it may even be desirable to increase the length of time to $1\frac{1}{2}$ or 2 minutes. Withey has shown that watertightness is increased by

longer mixing and there is some evidence to indicate that increased workability may also result. These recommendations are in accord with better practice at the present time, the usual limit for ordinary concrete operations being from 1 to $1\frac{1}{2}$ minutes after all the materials are in the mixer. For very large aggregates and in certain special types of work, still longer mixing times are frequently required.

Transporting Concrete

The method of transporting and distributing should be such as to deliver the concrete at the point of deposit in a uniform and homogeneous condition. The principal

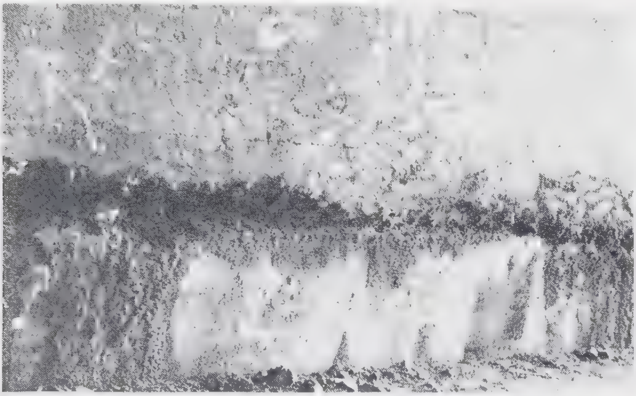

Fig. 29.—A section of wall 22 years old showing disintegration at the bottom of a section.

difficulty to overcome in any system is the tendency to segregation.

Under the practice of requiring a mix of fixed proportions, where changes in workability could be obtained only by changing the water content, the difficulties of segregation, both with chutes and with other methods, were greatly aggravated. Also, the quality of the concrete frequently suffered. Under the practice of designing mixes for definite quality through water control, not only can the quality be maintained but the proportions can be adjusted to give the greatest freedom from segregation no matter what system of transporting is used.

For transporting long distances, in cars, in trucks or in buggies, some separation of water from the mass can hardly be avoided even with comparatively stiff mixes. However, a general segregation of the different ingredients can be avoided by proper selection of the grading, proportions and consistency. If the placing requirements are such as to require mixes that do not transport without segregation, some means should be provided for remixing at the point of deposit.

The used of chutes for transporting concrete great distances has long been the subject of criticism on the basis of excess water and segregation. While much of this criticism has been justified owing to the poor concrete obtained, it must not be forgotton that the poor concrete was due to the manner of using the chute and is not directly chargeable to the chutes as such. It may be expected that many of the objections to the use of chutes will be withdrawn under the practice of holding to a fixed water-cement ratio. So long as assurance can be given that the mix will be delivered at the point of deposit with the required water-cement ratio and will meet the other requirements—uniformity, consistency, workability, and limiting proportions of sand—the method of transportation should be largely of only economic significance.

Vital Importance of Proper Placing

Of all the operations incident to construction, none is fraught with such consequences to the life of the structure as that of placing the concrete at the ultimate point of deposit. Too much emphasis cannot be placed upon the need for care in this respect, for much of the unsatisfactory concrete that exists today is in some measure chargeable to wrong or careless methods of placing, combined with non-workable or segregating mixes. Even with a well-designed mixture, properly mixed and delivered in a uniform, homogeneous condition, it is necessary to exercise care in depositing so that the concrete maintains its homogeneity as it is worked into the corners and angles of the

form and around the reinforcement. Any segregation or unbalancing of the mixture during this operation results

FIG. 30.—An example of carefully placed dry tamped concrete after 30 years exposure.

in a non-uniform condition from point to point which makes certain portions of the structure more susceptible to attack by the weathering agencies.

To avoid segregation, concrete should be of a plastic consistency just stiff enough to flow sluggishly when tamped or spaded, and should be distributed in shallow, even layers, working up to the full depth as the placing progresses. Flowing over long distances in the form will invariably result in some separation of the water and fines from the rest of the mass. If the mix is too stiff or too dry, it is difficult to bond successive layers and, in extreme cases, it

Fig. 31.—An eroded laitance seam in a dam less than 7 years old.

may even develop that the successive batches may not thoroughly unite. A desirable consistency is one that results in a slight accumulation of water at the top of the layer a few feet in thickness. If the depth of the layer is considerable, this accumulation of water will increase, and as the top of the lift is approached, the consistency should be stiffened to take up the excess water in the process of placing. Small amounts of accumulated water can be drained to a

low spot in the placing and be bailed or drained off. Large quantities of water, however, cannot be handled in this way because of the tendency to wash out desirable fines and cement.

Where the placing is to stop at what will be the upper surface of the wall or section, a very good practice is to overfill the form several inches, allowing the concrete to stand in this manner until the excess water has risen to the surface and drained off. The surface can then be screeded to the proper level. This method completely avoids both the laitance layer and the porous concrete immediately below. There are a number of examples of walls finished in this manner, the tops of which have remained in excellent condition after exposure for many years to very severe conditions. The results obtained in these cases are particularly noteworthy, for the usual condition is that structures in otherwise quite satisfactory condition show serious scaling or disintegration at the top surface. Even in thin slabs such as pavements, the same water gain can be seen where the surface has been overworked in finishing, and the effects of it are evident in many scaled surfaces.

Bonding Successive Layers

An important detail in placing concrete is securing the bond between successive layers. This is of special importance where watertight structures are intended. The difficulties to be encountered can be visualized by a casual inspection of any concrete surface placed against a form where no special effort was made, by spading or otherwise, to obtain complete contact of the concrete with the form. In the case of a horizontal surface between two layers, no opportunity is presented for working the spade along the surface to provide for the complete contact between the paste of the fresh concrete and the surface of the old. The practice of flushing a grout or thin mortar over the surface before starting the fresh con-

crete is a very desirable one, provided the mortar is not too thin and the placing of the concrete follows immediately upon the placing of the mortar. The thickness of the mortar layer required will depend upon the stiffness of the concrete and the size of the batch. For example, if 2-yd. buckets of very stiff concrete are being discharged on the surface, the depth of mortar coating should be an inch or more, while with concrete spread in thin layers, where an opportunity is afforded for a thorough working to insure contact, a much thinner coat should suffice. In any case, as soon as the placing is well started, so that a thoroughly bonded joint is assured, care should be taken to restore the proper consistency if the use of the mortar has made the mix too wet.

An important detail of the bonding is the character of the surface of the old concrete. This surface, of course, should be thoroughly cleaned and any laitance that may have formed should be removed. Too much emphasis cannot be placed on this matter of joints, for many structures in which the concrete has been otherwise satisfactory have developed leakage along the joints when subjected to direct water pressure.

Curing

The important part which curing plays in the building up of a solid structure, to resist the entrance of water and the effect of frost, has been amply stressed in the earlier chapters of this book. It is necessary to point out here only that making provisions for proper curing is one of the necessary construction operations. Proper curing means not only protection from the loss of water but also the maintenance of suitable temperature conditions. The curing requirements stated at the head of Table VII are amply justified where the concrete is to be exposed to the weathering agencies. If, for any reason, such curing condition cannot be obtained, richer mixes should be used.

FIG. 32.— Pine River Dam, Minn.
An example of carefully placed concrete after 21 years exposure.

Examples of Defects in Placing

A study of concrete structures which have been exposed for a number of years will show how the defects of placing are revealed by the process of weathering. Figures 27 and 28 are typical of many structures to be observed which are in the main serviceable after many years but which are badly scarred by the disintegration at points of weakness. Figure 27, which shows a dam in northern United States after 20 years of service, is a good example of disintegration resulting from improper placing and a wet consistency. It is typical, also, that the worst disintegration usually occurs in a buttress such as this or in a wing wall. This condition results from the practice of depositing the concrete in the body of the structure and allowing it to flow toward the ends and into the buttresses or wings carrying the excess water and laitance with it. It can be seen that much of the structure in Fig. 27 is in satisfactory condition. However, had more care been taken to place the concrete in uniform layers with a stiffer consistency, the entire mass could have been equally well preserved. Figure 28 is a picture of another structure in northern United States, built about 1913, which shows the same effect of the segregation due to the flowing of the concrete over long distances.

Figure 29 shows the disintegration of the concrete just above a construction joint. The wall in this picture was constructed in 1906 and is, in general, in excellent condition. The condition illustrated is typical of what happens when very dry mixes are attempted. The first batch above a joint is likely to be honeycombed due to the difficulty of molding a stiff mix into the sharp corners. The practice of placing a batch of mortar at the beginning of a lift will generally avoid this difficulty unless altogether too harsh or too stiff mixes are being used. Dry mixes require careful placing and thorough ramming to avoid air pockets and porous condition generally.

Figure 30 is an especially interesting example of a concrete structure in which a very dry mix was used but which

was carefully placed and thoroughly rammed. This dam, which is more than 30 years old, is in a most excellent condition. It will be noted that the various layers are quite distinctly marked as a result of the scaling which has taken place at the lower edge of each layer. This shows the difficulty of getting a perfect filling of the concrete into the sharp angles where the dry tamped mixes are used. It also shows that, except for these slight imperfections, the concrete placed by these methods is durable to a high degree.

Figure 31 is an illustration of a particularly flagrant case of segregation and overwet mixes. The large cavity which shows running through the center of this picture is an eroded laitance seam which is as much as 6 in. thick in places and eroded back 2 ft. or more. Just above this cavity will be seen a patch of concrete in which the coarse aggregate greatly predominates, while to the left of this point is a considerable area in which almost no coarse aggregate is to be found. Just below the laitance seam also there is a deficiency in coarse aggregate. This structure is less than 7 years old.

The dam in Fig. 32 is an outstanding example of the success attained by careful workmanship. This structure, which is one of the control dams built by the U. S. Engineer Corps, at the headwaters of the Mississippi River near Pine River, Minn., has stood 21 years in severe exposure without showing any evidences of disintegration. In placing this structure a consistency was used that required some tamping but which also yielded some excess water under the tamping. This excess was soaked up from time to time as the placing progressed by working into the mortar layer an additional amount of coarse aggregate. The excellence of this structure will be apparent from a close study of the illustration. It is a wonderful tribute to intelligent and careful supervision.

It is interesting to consider these examples of structures in the light of the earlier discussions of this text. Such a study will show that those structures or portions of struc-

tures which have withstood the destructive forces of weathering are those in which all the space between the aggregate particles is thoroughly filled with a cement paste of low water-cement ratio. Also wherever the space between the aggregate particles has not been filled, or where the paste has been weak and porous, due to large excess of water, those portions of the structure have weathered away.

Concluding Remarks

This text would not be complete without some word regarding the responsibility for good concrete construction.

Too often individuals in ultimate authority have the desire for concrete of the proper quality, but fall short of attaining it through failure to delegate the necessary authority and to fix the responsibility for results. It is not uncommon to find a construction superintendent in a position to ignore the recommendations of the engineer where, in his opinion, they impede the progress of the work or increase the cost. If, under such conditions, quality is subordinated to first cost, durable structures cannot be expected.

There must be a recognition by those in authority that uniform concrete of good quality requires intelligent effort and faithfulness to details all along the line—proper materials, proper design, proper mixing and transporting, and special care in placing and protecting. It must be recognized that to obtain the desired results some qualified person must be made responsible for these details, and having been made responsible, must be intrusted with the necessary authority.

It must not be assumed that because it requires well-directed effort to produce uniformly good concrete the cost is necessarily increased. There have been any number of examples in recent years where rigid control of the concreting operations not only has given concrete of the required quality but has shown a distinct saving in *first cost* as compared with earlier experiences in which

only indifferent or unsatisfactory results were obtained. But even if the first cost is increased by the requirements for definite quality, the ultimate cost which must include maintenance and repair charges will be greatly decreased. In support of this statement, if support is needed, a number of examples can be cited where the expenditures for maintenance and replacements have been many times the amount which would have been necessary to insure the highest quality of concrete at the time of original construction.

A comparison of Figs. 31 and 32 gives a good illustration of the investment value of good concreting methods. Figure 31 shows a structure but a few years old that is already in need of major repairs and may shortly require almost complete rebuilding. In this structure almost every requirement for good concrete seems to have been violated. Figure 32, on the other hand, shows a structure in which care was taken in all the operations. It is still in perfect condition after 21 years in an exposure more severe than that to which the structure of Fig. 31 is subjected. It needs only the briefest consideration of such a contrast as that presented by these two structures to realize how immensely productive in increased life and reduced maintenance charges a few extra dollars can be when spent to secure suitable mixtures and careful placing.

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